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WANL-PR-953074-14

Westinghouse Astronuclear Laboratory

STUDY OF THE COLLECTOR/HEAT PIPE COOLED EXTERNALLY CONFIGURED THERMIONIC DIODE

FINAL REPORT

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Astronuclear
Laboratory

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March 6, 1973

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FINAL REPORT

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

APPROVED BY:

J. M. Ravets, Manager
Thermionics Project

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FOREWORD

This is the final report for the Collector/Heat Pipe Cooled Externally Configured Thermionic Diode Study performed for the Jet Propulsion Laboratory under JPL Subcontract No. 953074, Prime Contract NAS 7-100. Mr. G. M. Kikin (JPL) was the Technical Program Manager. Mr. Kikin's efforts in guiding the program and supplying much valuable technical input, which was used in this study, are gratefully acknowledged, as is the assistance of Messrs. J. Kemme and J. Deverall of the Los Alamos Scientific Laboratory.

I. SUMMARY

A collector/heat pipe cooled, externally configured (heated) thermionic diode module was designed for use in a laboratory test to demonstrate the applicability of this concept as the fuel element/converter module of an in-core thermionic electric power source. During the course of the program, this module evolved from a simple experimental mock-up into an advanced unit which was more reactor prototypical.

Detailed analysis of all diode components led to their engineering design, fabrication, and assembly, with the exception of the collector/heat pipe. While several designs of high power annular wicked heat pipes were fabricated and tested, each exhibited unexpected performance difficulties. It was concluded that the basic cause of these problems was the formation of "crud" which interferred with the liquid flow in the annular passage of the evaporator region. LASL experience indicated that crud buildup is especially severe when stainless steel is used as the heat pipe structural material and that the deleterious effects of this crud are most pronounced in heat pipes having small annular liquid flow passages.

This report describes the design approach followed and the results of the analysis leading up to the reference thermonic module designs, both "initial" and revised (or "final"). Engineering layout drawings for components of both modules are given. The various steps taken in the component fabrication and the module assembly are detailed. While the testing and experimental portions of the program were not completed, the report describes the items in these areas that were accomplished.

Since the collector/heat pipe development played so important a role in this program, the analysis, design, development, fabrication and testing of these annular heat pipes are separately treated. While these efforts did not produce a heat pipe that could successfully transfer the large heat flux required for the postulated in-core thermonic reactor application, it is believed that the information obtained from this study could contribute towards the

development of a high performance heat pipe.

II. INTRODUCTION

Collector/heat pipe cooled, externally configured thermionic diode modules formed the core of a 300 Kwe reactor designed during previous contract effort.[1] The dimensions of these modules were selected based on the results of thermal, electrical, nuclear, and shielding optimization studies. The reactor employed full-length double-ended diodes, each cooled by a single high performance heat pipe. The diodes were arranged in clusters of six, forming a core with a 0.4 length-to-diameter ratio. A schematic of this reactor concept is shown in Figure 1. The design parameters of the reactor module are listed in Table 1.

The diode module to be designed, fabricated, and tested for this program simulated one-half of the double-ended reactor diode. It was decided to deviate somewhat from the exact reactor module dimensions for the experimental test article in order to employ off-the-shelf hardware for the construction of the diode. The objectives of the experiment would not be compromised by this approach. Indeed, the use of stock tubing would help insure emitter-collector alignment as it could be obtained nearly straight and strain-free. Accordingly, a modified diode module design was formulated for experimental testing. The design parameters of the experimental module are also listed in Table 1.

The use of a heat pipe/collector to remove heat from an in-core diode made this project unique relative to other diode experimental programs. In the Westinghouse thermionic reactor design, the heat pipe cools the diode and the heat pipe wall serves as the collector. When reactor diode performance is optimized, the collector/heat pipe is required to transport about 3.5 kw of heat from each diode with a collector geometry that is unfavorable to heat pipe operation, i.e., relatively long with relatively small diameter. The heat pipe must have excellent wicking characteristics and minimum liquid pressure drop in order to satisfy the cooling requirements. An annular liquid passage for circulation of the liquid working fluid using a heterogeneous wick (wick and liquid in separate regions) was therefore selected as the heat pipe wick configuration.

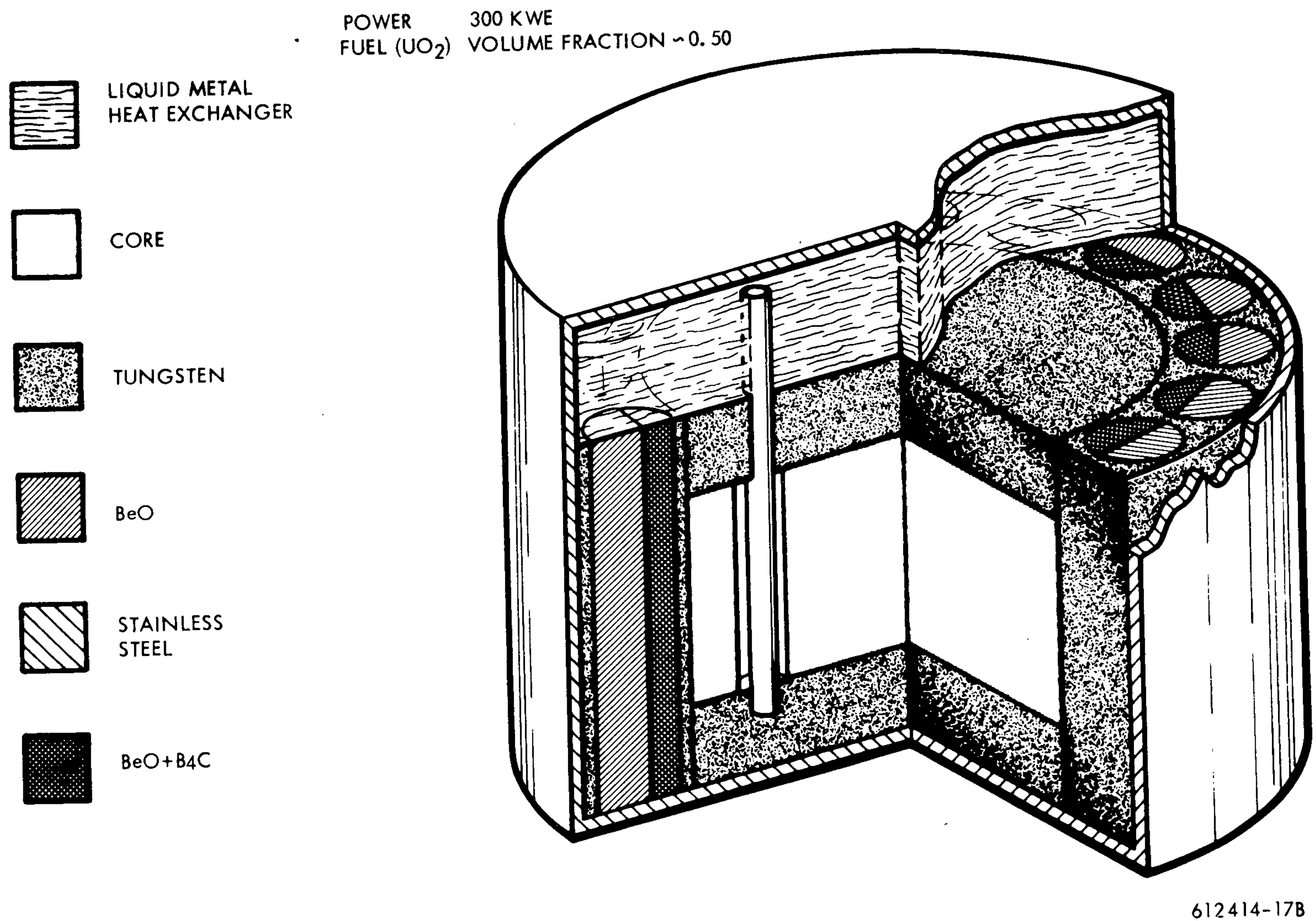

Figure 1. Schematic of T/I Reactor Employing Double-Ended Diodes

TABLE 1

DIODE MODULE DESIGN PARAMETERS

	Reactor Module	Experimental Module
Diode Length, Inches	4.8*	5
Emitter		
Material	W	T-111
OD Inches	0.535	0.625
ID Inches	0.435	0.505
Collector/Heat Pipe		
Material	Nb-1Zr	Stainless Steel
Working Fluid	K	Na
H. P. Wall OD, Inches	0.415	0.485
H. P. Wall ID, Inches	0.375	0.439
Restrainer OD, Inches	0.315	--
Restrainer ID, Inches	0.295	0.409**
Restrainer Void, %	50	31***
Screen	500 mesh	500 mesh

*Half-length of double-ended diode

**Used swaged wick without restrainer, yielding 0.409 inch vapor diameter.

***Swaged wick had 69% density.

Figure 2 illustrates the interior components of a heterogeneous wicked (annular gap) heat pipe.* With a heterogeneous wick, an annular liquid flow passage is formed by the heat pipe wall at the OD of the annulus and the wick at the ID of the annulus.

It was initially considered desirable to plate the stainless steel heat pipes with nickel to better simulate the thermionic properties of the Nb-1Zr collector material to be used in the reactor. Subsequent materials investigations defined problems that could possible arise from Ni contamination of the refractory metal collector during assembly or operation. Thus, with JPL approval, the heat pipe was not plated.

Using the diode module described in Table 1, this experimental study was to carry out four basic tasks to provide:

- A JPL-approved design of a Collector/Heat Pipe Cooled Externally Configured Thermionic Diode.
- Fabrication of such a diode, including associated test instrumentation.
- Testing of the diode/heat pipe using existing facilities, in accordance with a JPL-approved Test Plan
- Experimental determination of diode operating characteristics and comparison to analytical performance predictions.

Because of difficulties which arose in developing the required high performance heat pipe, the last three items were not completed.

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*Early heat pipes built for this program were of the Figure 2 configuration, which was the reactor study[1] design; i.e., they employed a wick restrainer. The later pipes had similar liquid flow annuli, but used swaged wicks and no restrainers, as shown in Figure 9 and described in Table 3.

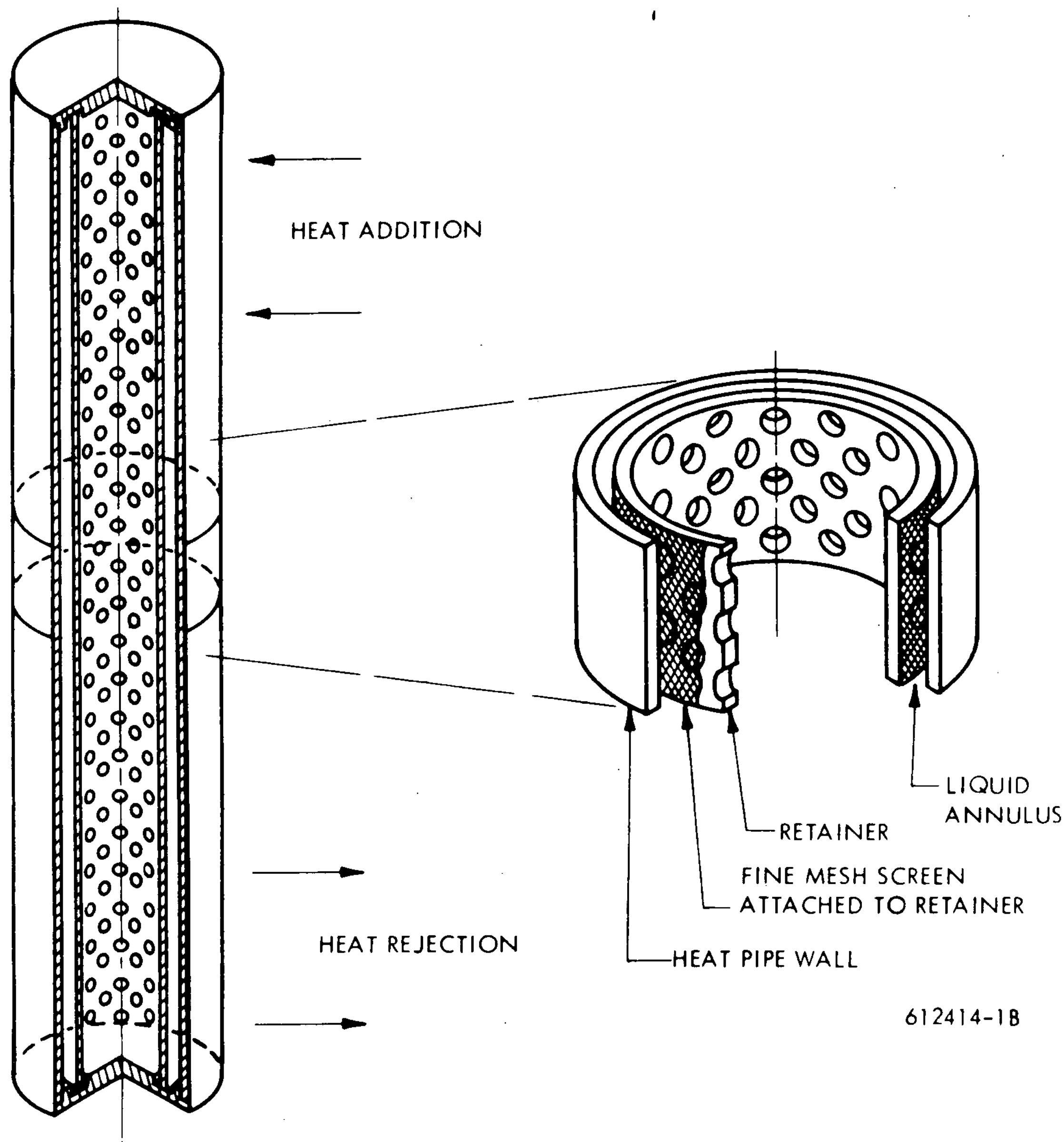

Figure 2. Schematic of WANL Heat Pipe

B

III. APPROACH

During the program, Westinghouse succeeded in performing much of the effort required for the four major tasks previously noted. Following JPL redirection of effort, the program actually had two phases: Initial Program and Revised Program. While the basic diode designs were quite similar in the two phases, the explicit designs and materials of the primary components - heat pipe and emitter - differed.

III. A. Initial Program

The initial program involved design and fabrication efforts leading to the development of a diode employing a stainless steel annular wicked heat pipe and a CVD-W emitter. The annular gap in the heat pipe was increased [(2)] from the 0.009" nominal Westinghouse design to 0.027" to better simulate the I^2R drop that would exist in the reactor heat pipe. This latter heat pipe assumed use of a Nb-1Zr wall and K working fluid, yielding a much better electrical conductivity than would be obtained with a stainless steel wall, Na fluid heat pipe of the same dimensions.

The initial design involved the use of Nb-1Zr flexure pieces and ceramic to metal brazed joints. While the resulting configuration was not reactor prototypical, the several diode components would be compatible with the test conditions, resulting in a diode that could be tested in the Westinghouse diode test facility (test rig). Effort for this portion of the program involved design, analysis, and component fabrication and testing.

III. B. Revised Program

The CVD tungsten emitter and collector/heat pipe assembly drawings formed a Design Package that was critically reviewed by JPL. As a result of this review, JPL requested design modifications which would make the diode more prototypical of a reactor module. These were reviewed in a meeting at Westinghouse with Mr. G. M. Kikin, JPL Technical Program Manager. These design modifications were:

(1) Replace the Westinghouse "hat" seal (see Figure 13) with the Nb-1Zr to Al_2O_3 to Nb-1Zr seal developed by GGA.

(2) Thicken the emitter by increasing its OD

(3) Thicken the collector/heat pipe OD in the region above the diode.

(4) Eliminate the saphire spacer beads and replace them with zirconia split bushings held in place by rhenium wires

(5) Modify the emitter (bottom) power take-off lead to insure good electrical contact.

The assembly drawings were modified to take into account all of these suggestions. This formed the first of two major sets of modifications in the Revised Program. In addition, to meet schedule and cost limitations, it was decided to use a T-111 emitter as the test diode component.

As a result of the difficulties encountered in fabricating a high performance heat pipe having the desired ($\sim$3.5 Kwt) heat throughput capabilities, the program was again redirected. A technical review of the program by JPL and WANL culminated in the formulation of a JPL Technical Direction Memorandum[3] directing WANL to proceed along a specifically defined course of effort that was within general scope of the contract and had the highest probability of meeting the contract goals.

In particular, the memorandum required the design, fabrication, and testing of a 6 mil annular, sodium charged heat pipe for use as the diode collector element. For diode operation in a zero gravity environment, this heat pipe configuration was believed (by JPL and WANL) to be the best direction to proceed in order to product the desired high power Collector/Heat Pipe.*

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*This decision largely evolved from review of the successful performance of a similar heat pipe designed and operated by J. Kemme of LASL.

The heat pipe of the revised program would include:

- Sodium as the working fluid
- 347 Stainless Steel heat pipe tube
- 347 Stainless Steel (1st choice) or 304 Stainless Steel (2nd choice) for capillary mesh screen
- Annular liquid gap to be ~0.15 mm (.006 in.)
- Positive screen spacers to be employed to maintain 0.15 mm annular gap concentricity
- Capillary screen mesh welded closed at evaporator end, and crimped closed at condensor end
- Use of zirconium foil getter in heat pipe
- Incorporation of sump in heat pipe design
- Stainless Steel bellows seal valve on fill tube line
- Dry, inert-gas atomsphere to be maintained around the portion of heat pipe extending outside of diode test rig.

Because of the importance of developing high performance heat pipes, JPL arranged to have heat pipes built for this program tested at LASL. Since LASL was in the forefront of heat pipe design and development, it was believed that their review of the design and actual testing of the heat pipes might resolve some of the problems encountered. Heat pipes with both the original (0.027") and revised (0.006") gap construction were delivered to LASL, where they underwent a series of tests. The experiments with the latter pipe were in progress at the termination of Westinghouse technical effort on this contract.

IV. TECHNICAL DISCUSSION

This section provides a detailed description of the technical effort aimed at carrying out the goals of this study, for both the Initial and Revised Designs. Because of its importance to the program and the degree of expended effort thereon, the Heat Pipe work is discussed separately from the diode effort, although it is, of course, a basic diode component. The diode effort will be described according to Contract Task number.

IV. A. Diode

To meet the objectives of this program, Westinghouse was to perform analytical/design (Task 1), fabrication (Task 2), testing (Task 3) and experimental investigation (Task 4) of a Collector/Heat Pipe Cooled Externally Configured Thermionic Diode to demonstrate the feasibility of such a device. Much of this required effort was successfully completed but, because of the heat pipe problems, all of the above tasks were not carried to completion. The diode effort is described below.

IV. A. 1. Task 1 - Diode Design

As part of the Initial Program, Westinghouse provided JPL with a description of the diode test facility (see section IV. A. 4, Task 3 - Testing) to be used in this project. The early effort was directed at developing a diode using a CVD-W emitter that was compatible with the test rig.

A preliminary engineering layout of the Initial Design diode configuration (Figure 3) based on mechanical, material and thermal analyses, was formulated. A $50^{\circ}K$ temperature falloff at the end of the emitter was used in this analysis, giving an emitter end temperature of $1950^{\circ}K$ for the nominal $2000^{\circ}K$ emitter operating temperature. This required use of a heat choke above the emitter to reduce the temperature on the "hot" side of the insulator to a desired $900^{\circ}C$ ($1173^{\circ}K$). Part of this choke was fabricated by welding two Nb-1Zr "hat" shaped pieces. The flexure of these pieces reduced the thermal stress in the insulator braze. It was envisioned that the Nb-1Zr brazed piece on the "cold" side of the insulator would be joined to the stainless steel bellows by means of a Nb-1Zr -to-stainless

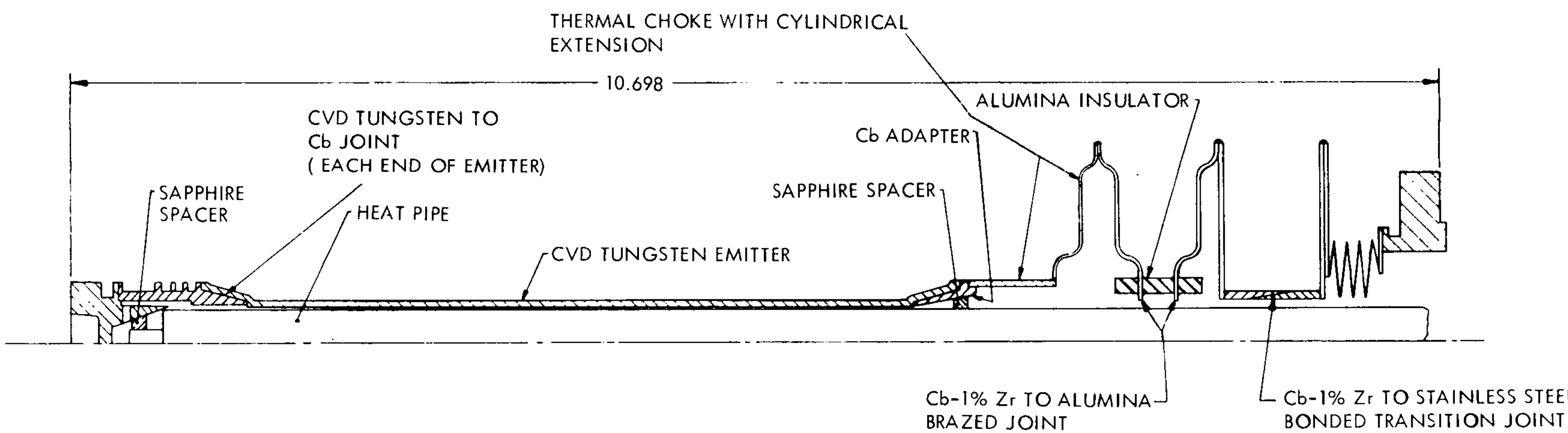

Figure 3. Thermionic Diode Layout

steel transition piece. Alternatively, the possibility of brazing the "cold" side Nb-1Zr insulator end piece directly to stainless steel was also investigated.

The detail design of the CVD tungsten emitter assembly was established. It was planned to form the emitter proper on Ta-10W end adapters by means of chemical vapor deposition. Prints of the CVD tungsten emitter and collector/heat pipe assembly drawings, Figures 4 through 7, were sent to JPL in fulfillment of the Design Package milestone (Task (1) (D)). In addition, labeled prints of the test chamber assembly drawings were included in the Design Package submittal.

These drawings incorporated Nb-1Zr to 316 stainless steel transition joints. Investigations showed that this would be preferable to a direct brazing of the refractory to ferritic metal components.

As previously discussed, the above Initial Design configuration was (at JPL direction) abandoned in favor of the Revised Design which would yeild a diode more prototypical of the reactor module. Although such a design was not initially considered to be essential to the program, JPL subsequently believed that the long range efforts to develop a thermionic reactor would be sufficiently furthered by this redirection to justify modification of the program (see Section III).

The design modifications* requested by G. M. Kikin (JPL), were incorporated into the diode design. Detail and assembly drawings (Figures 8 through 11, inclusive) were prepared and reviewed by JPL. Both the T-111 and CVD-W emitters were under consideration at this point, though only the T-111 diode components were later fabricated and assembled.

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*Enumerated on page 3-2.

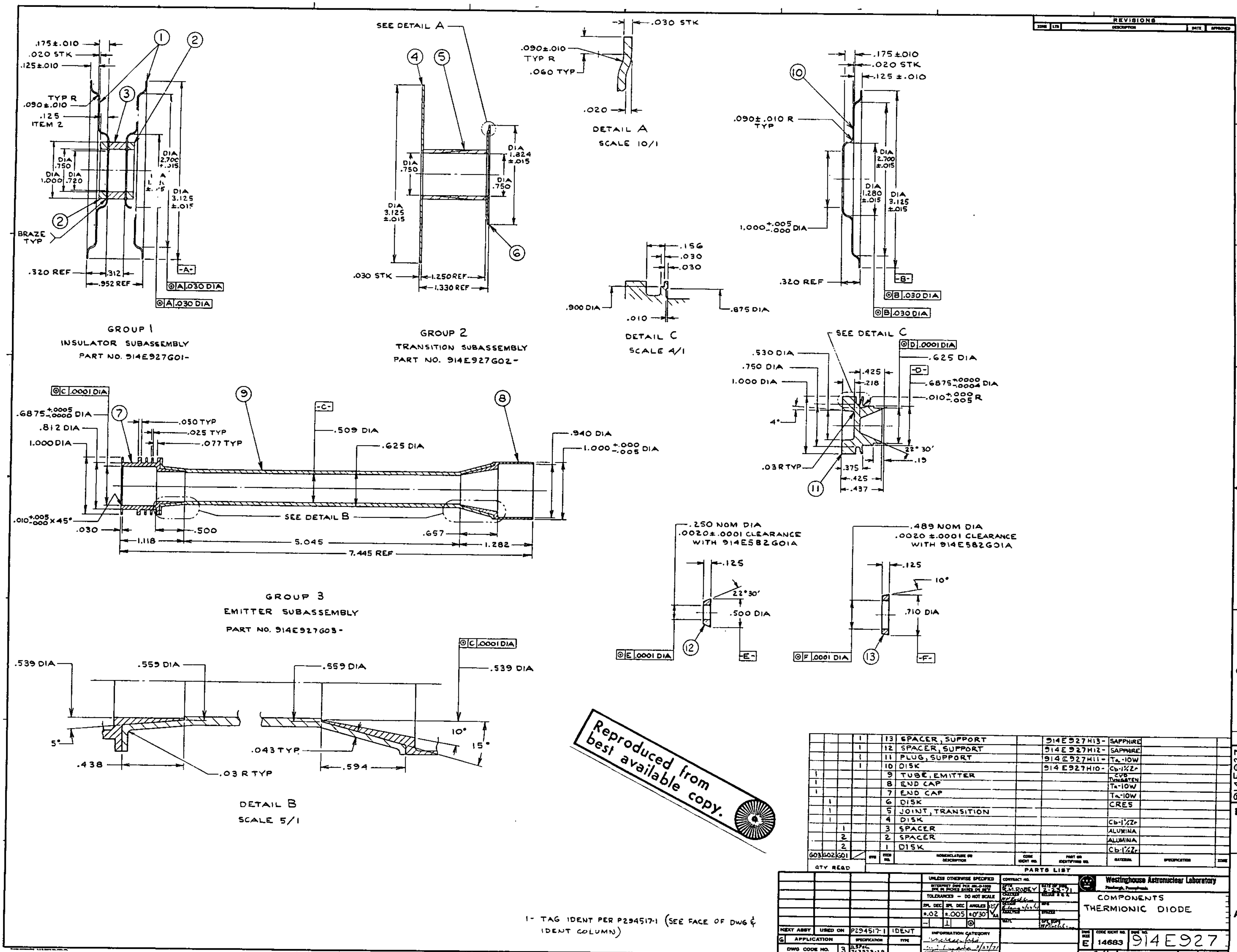
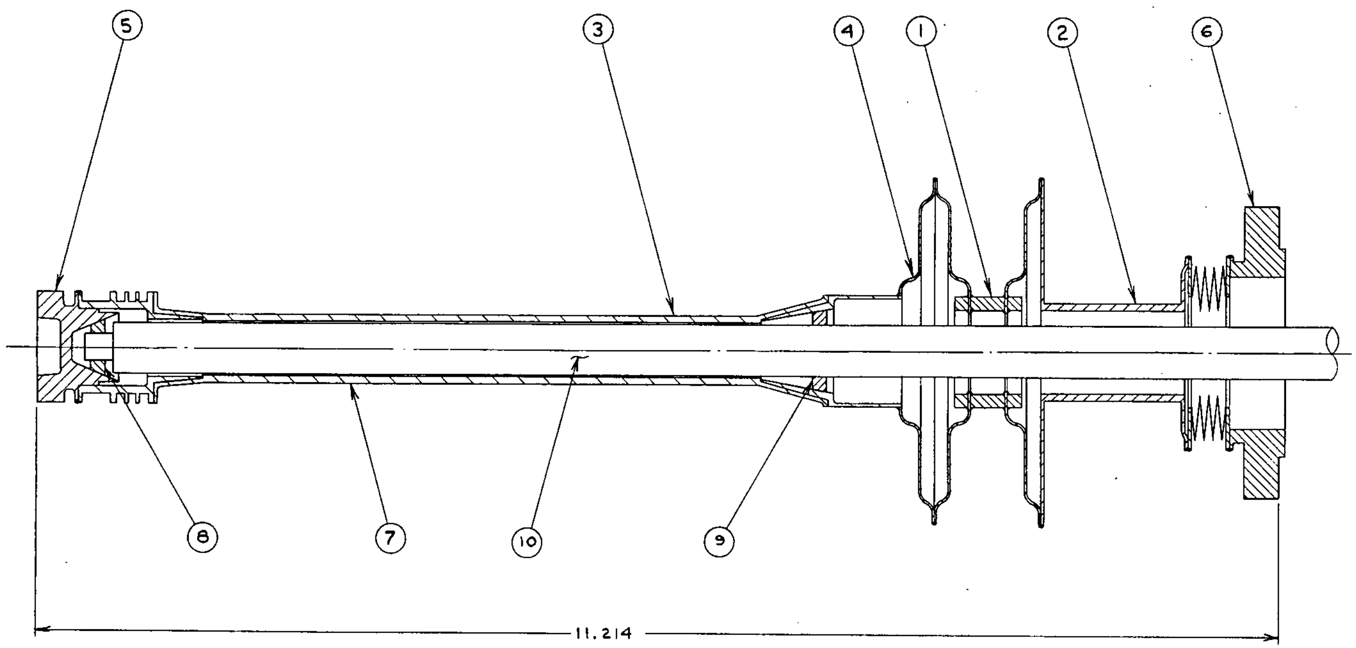


Figure 4. T-111 Diode Components (Dwg. 914E927)



GROUP 1

THERMIONIC DIODE ASSEMBLY

PART NO. 982D228G01-

1- TAG IDENT PER P294517-1 (SEE FACE OF DWG)

QTY REQD G02	QTY REQD G01	SYM	ITEM NO.	NOMENCLATURE OR DESCRIPTION	CODE IDENT NO.	PART OR IDENTIFYING NO.	MATERIAL	SPECIFICATION	ZONE
	1		10	PIPE, HEAT		914E582G01A			
	1		9	SPACER, SUPPORT		914E927H13-			
	1		8	SPACER, SUPPORT		914E927H12-			
	1		7	ASSEMBLY, EMITTER		982D228G02-			
1			6	SUBASSEMBLY, BELLOWS		982D229G01-			
1			5	PLUG, SUPPORT		914E927H11-			
1			4	DISK		914E927H10-			
1			3	SUBASSEMBLY, EMITTER		914E927G03-			
1			2	SUBASSEMBLY, TRANSITION		914E927G02-			
1			1	SUBASSEMBLY, INSULATOR		914E927G01-			

PARTS LIST

NEXT ASSY | USED ON | P294517-1 | IDENT

B | APPLICATION | SPECIFICATION | TYPE

DWG CODE NO. 3 | D.SPEC. 763923-2B

UNLESS OTHERWISE SPECIFIED — INTERPRET DWG PER MIL-D-1000 DIM IN INCHES BASED ON 68°F — TOLERANCES – DO NOT SCALE — 2PL DEC ± — 3PL DEC ±.005 — ANGLES ±

INFORMATION CATEGORY Unclassified — AUTHORIZED CLASSIFIER DATE 2/24/71

CONTRACT NO. — DFTN R.M. ROBEY — DATE OF DWG 2-23-71 — CHECKER — RELIAB & Q. A. — DESIGN 2/19/71 — MFG — ANALYSIS — STRESS — MATL — ENGRG APPD

Westinghouse Astronuclear Laboratory, Pittsburgh, Pennsylvania

ASSEMBLY THERMIONIC DIODE

DWG SIZE D | CODE IDENT NO. 14683 | DWG NO. 982D228

SCALE 2/1 | WT ACT. | WT CALC | SHEET 1 OF 1

Figure 5. CVD-W Diode Assembly (Dwg. 982D228)

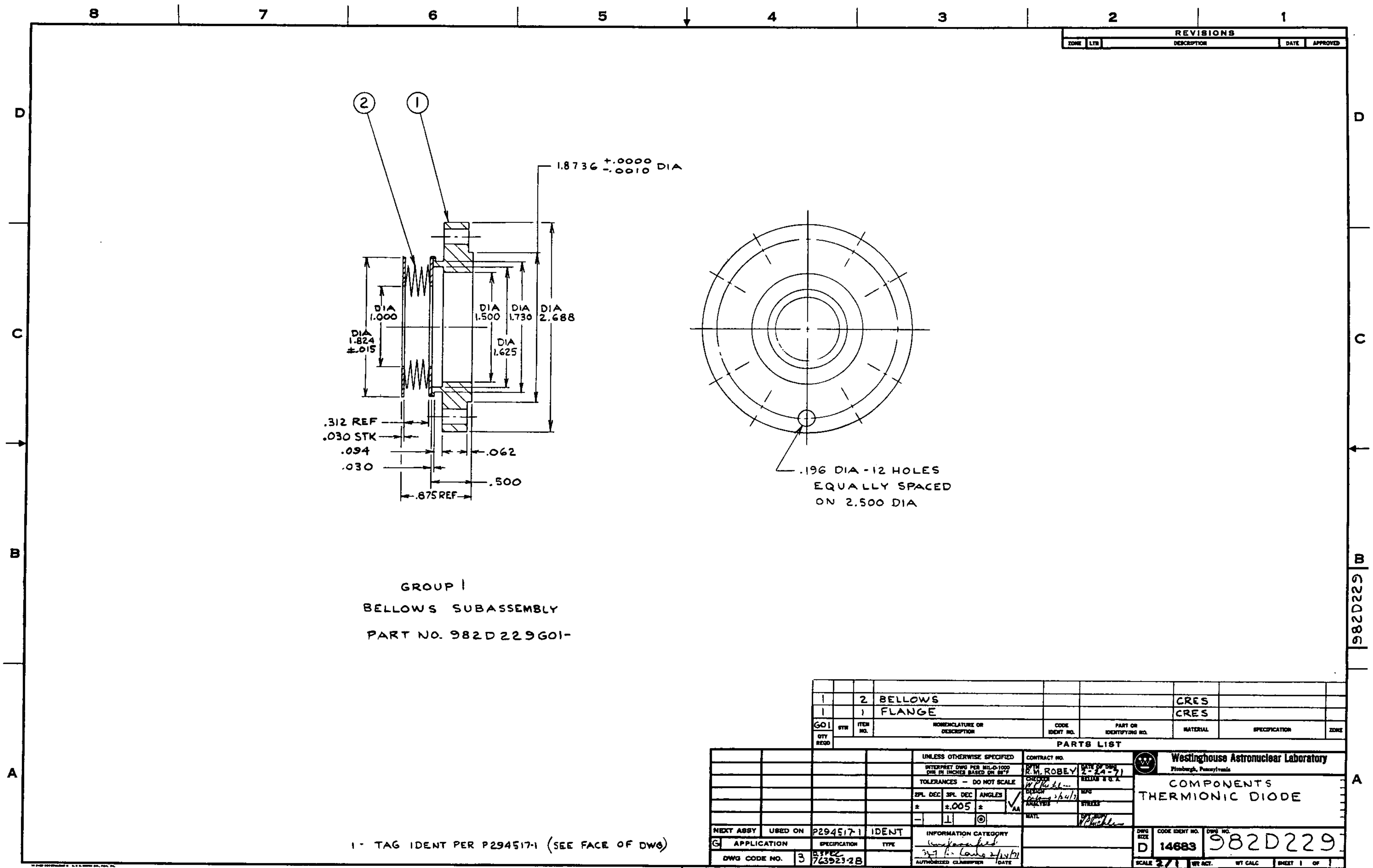
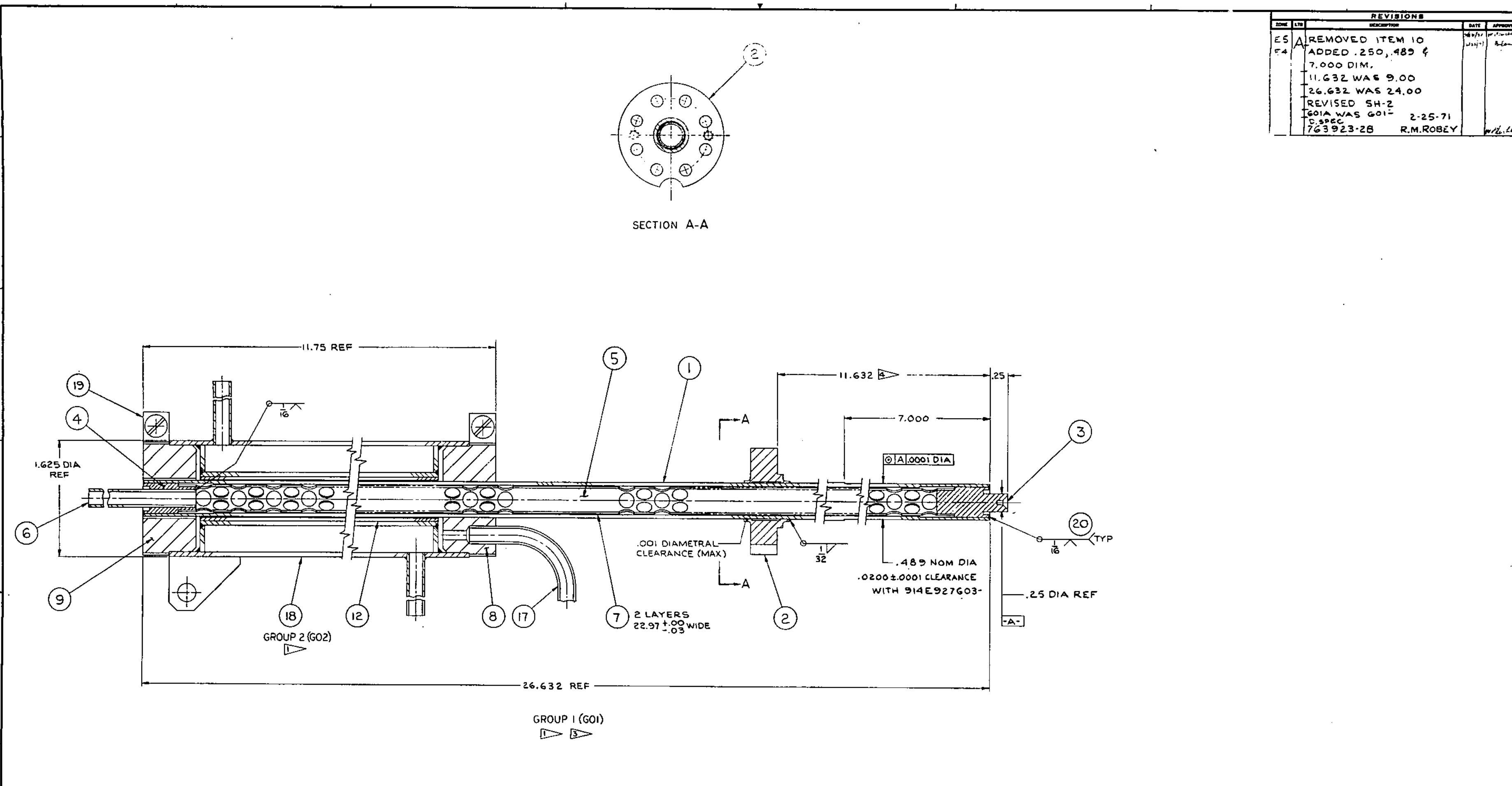


Figure 6. Bellows Subassembly (Dwg. 982D229)



4 FLANGE (IT. 2) TO BE ⊥ TO OUTER TUBE (IT. 1) WITHIN .002 MAX RUN OUT AFTER WELDING FOR 11.632 DIM.

3 ENTIRE ASSEMBLY TO BE STRESS RELIEVED BEFORE FINAL MACHINING AND INSTALLATION OF CALORIMETER ASSY (GROUP 2).

2 PURCHASE FROM AEROQUIP/MARMAN DIVISION LOS ANGELES, CALIF 90064 OR EQUAL.

1 GROUP 1 (G01) IDENTIFIED BY 914E582G01A.
GROUP 2 (G02) IDENTIFIED BY 914E582G02-.

G02	G01A	SYM	ITEM NO.	NOMENCLATURE OR DESCRIPTION	CODE IDENT NO.	PART OR IDENTIFYING NO.	MATERIAL	SPECIFICATION	ZONE
	AR		20	ELECTRODE			CRES	E308-15	
	2	2	19	BAND CLAMP		MB9802-8-150-38			
	1		18	CALORIMETER ASSY		914E582G02-			
	1		17	TUBE		914E582H17-	CRES	AISI 304	
2			16	END PLATE		914E582H16-	CRES		
3			15	LUG		914E582H15-	CRES		
1			14	TUBE		914E582H14-	CRES		
1			13	TUBE		914E582H13-	CRES		
1			12	SLEEVE		914E582H12-	CRES		
2			11	TUBE		914E582H11-	CRES	AISI 304	
	1		9	INSULATOR		914E582H09-	ALSIMAG 222		
	1		8	INSULATOR		914E582H08-	ALSIMAG 222		
	AR		7	SCREEN-508 MESH-.0010 WIRE DIA		914E582H07-	CRES	AISI 304	
	1		6	TUBE, DEGASSING		914E582H06-	CRES		
	1		5	RETAINER		914E582H05A	CRES		
	1		4	END CAP		914E582H04-	CRES		
	1		3	END CAP		914E582H03-	CRES		
	1		2	FLANGE		914E582H02-	CRES		
	1		1	TUBE, OUTER		914E582H01A	CRES	AISI 304	
QTY REQD									

LIST OF MATERIALS

Westinghouse Astronuclear Laboratory
Pittsburgh, Pennsylvania

THERMIONIC HEAT PIPE

CONTRACT NO. 6-53319-787B
B. CHLASTA 4-28-65
UNLESS OTHERWISE SPECIFIED
TOLERANCES - DO NOT SCALE
2PL DEC ±.02 | 3PL DEC ±.002 | ANGLES ±2°
NEXT ASSY | USED ON: P294517-1 | APPLICATION
IDENT
UNCLASSIFIED
DWG CODE NO. 3 D763835-1A
E 14683 914E582
SCALE 2/1 SHEET 1 OF 2
REV A A
SHEET 2 1
REV STATUS OF SHEETS

Figure 7. Heat Pipe (0.027 inch I.D.) with Calorimeter (Dwg. 914E582)

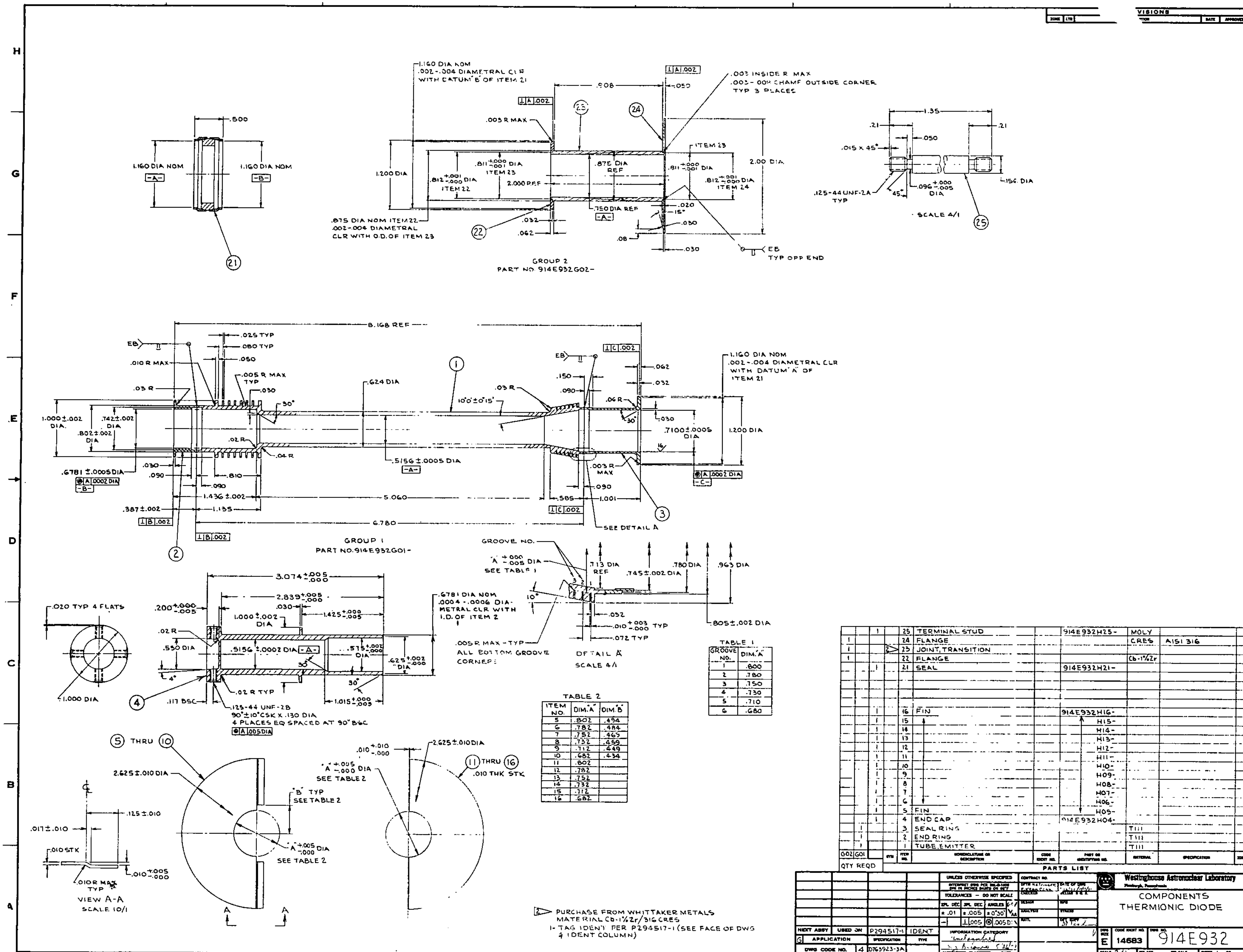


TABLE 1

GROOVE NO.	DIM. "A"
1	.800
2	.780
3	.750
4	.730
5	.710
6	.680

TABLE 2

ITEM NO.	DIM. "A"	DIM. "B"
5	.802	.494
6	.782	.484
7	.752	.465
8	.732	.459
9	.712	.449
10	.682	.434
11	.802	
12	.782	
13	.752	
14	.732	
15	.712	
16	.682	

PARTS LIST

ITEM NO.	NOMENCLATURE OR DESCRIPTION	PART OR IDENTIFYING NO.	MATERIAL	SPECIFICATION
25	TERMINAL STUD	914E932H25-	MOLY	
24	FLANGE		CRES	AISI 316
23	JOINT, TRANSITION			
22	FLANGE		Cb-1%Zr	
21	SEAL	914E932H21-		
16	FIN	914E932H16-		
15		H15-		
14		H14-		
13		H13-		
12		H12-		
11		H11-		
10		H10-		
9		H09-		
8		H08-		
7		H07-		
6		H06-		
5	FIN	H05-		
4	END CAP	914E932H04-		
3	SEAL RING		T111	
2	END RING		T111	
1	TUBE, EMITTER		T111	

Figure 8. Revised T-111 Diode Components (Dwg. 914E932)

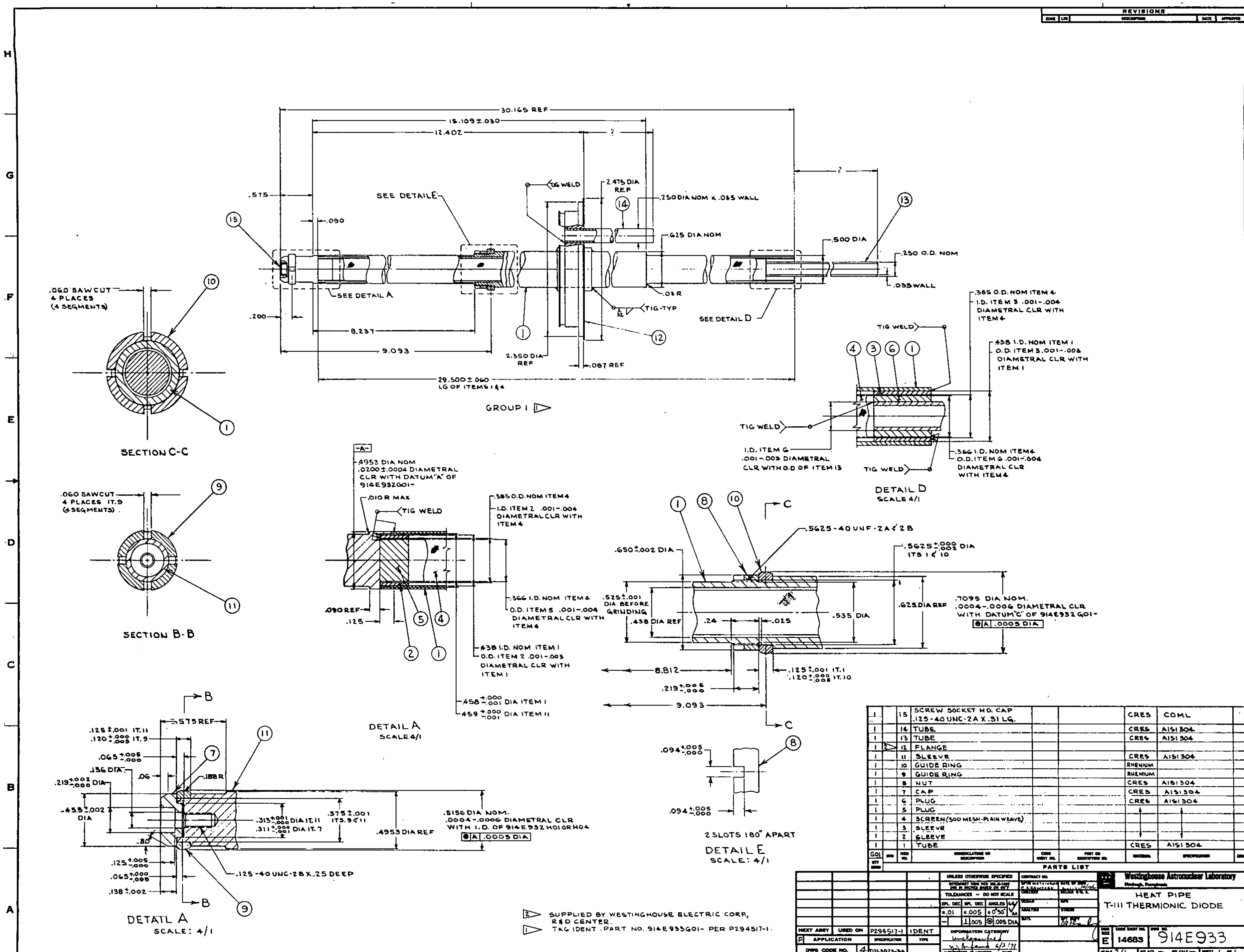


Figure 9. Heat Pipe (0.027 inch I.D.) for T-111 Diode (Dwg. 914E933)

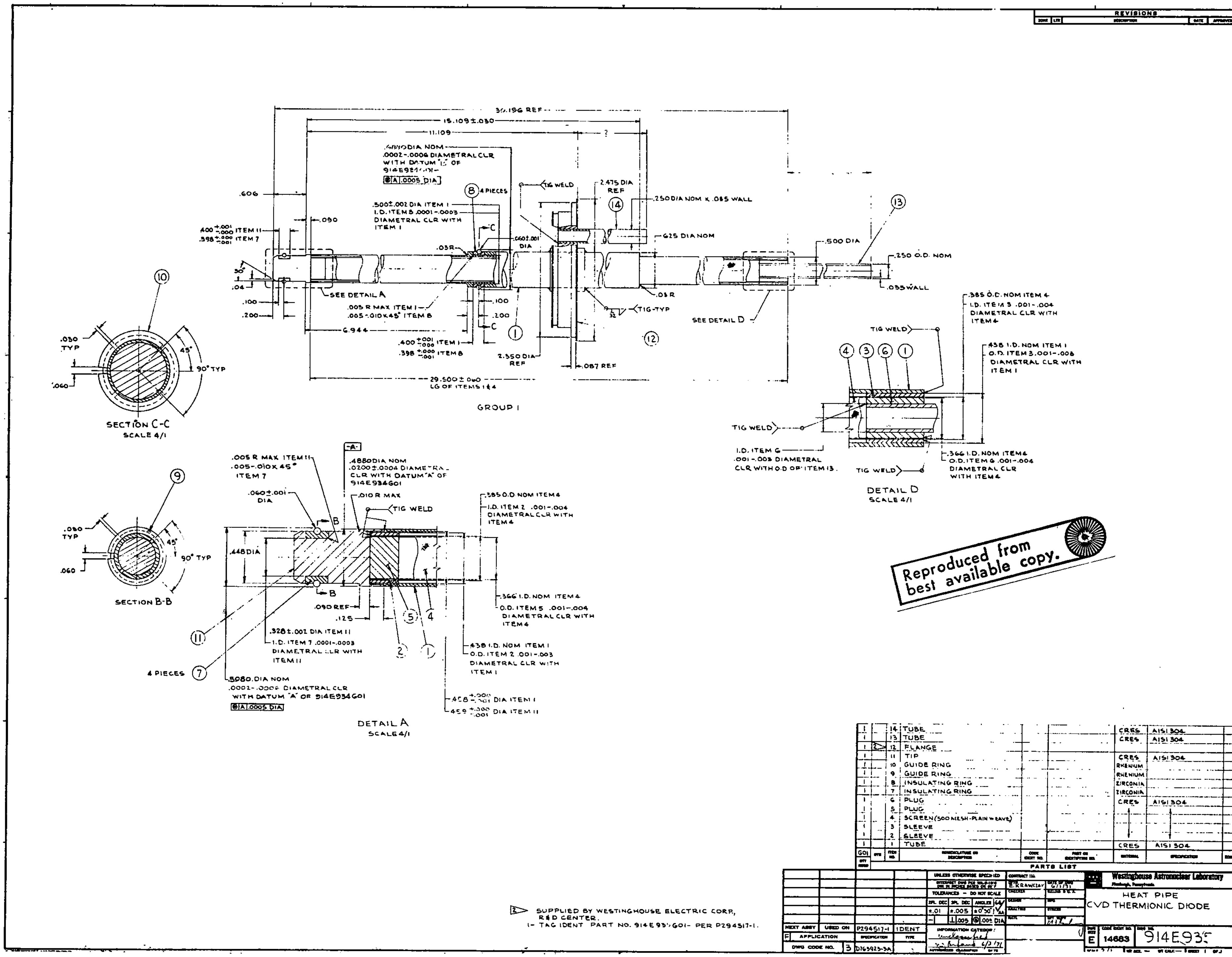


Figure 10. Heat Pipe (0.027 inch I.D.) for CVD-W Diode (Dwg 914E935)

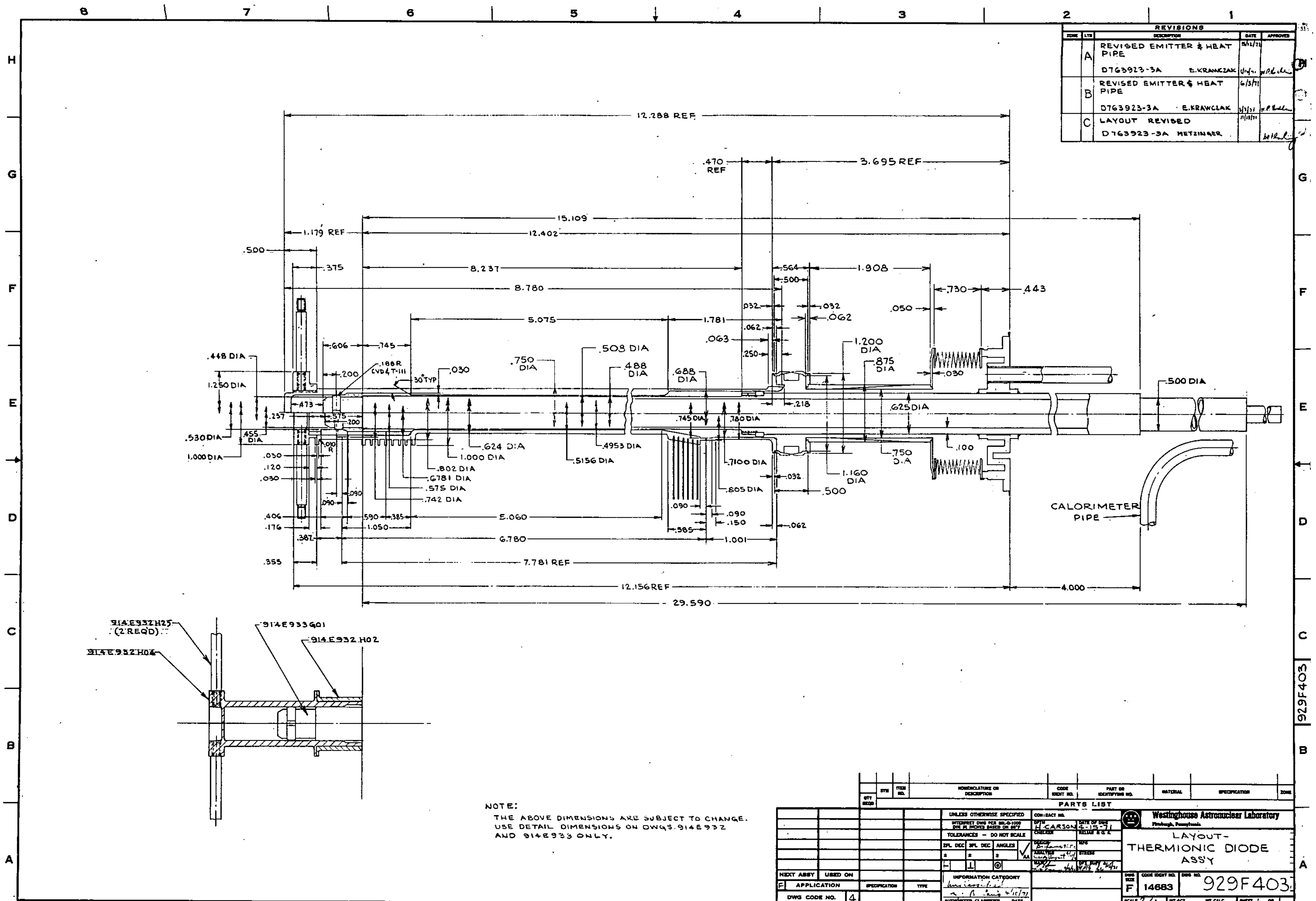


Figure 11. Layout of T-111 and CVD-W Diode Assemblies (Dwg. 929F403)

In addition to the modifications recommended by JPL, these revised diode layout drawings included the following changes:

- The emitter bottom closure was made in one piece to avoid an EB joint which would have to maintain its integrity and remain leak tight during long term operation at temperatures as high as 2000°K in a cesium environment.
- An extension was added at the bottom of the heat pipe to provide a small sodium reservoir. The emitter bore was enlarged around the heat pipe extension to avoid thermionic emission heating of the reservoir and the inactive end of the pipe.

To utilize the GGA seals in the modified design which eliminated the "hat" pieces, an alternative "thermal choke" was incorporated into this design. A thermal analysis was performed to determine acceptable dimensions of this choke. Two cases were examined: (1) a CVD-W piece which would be an extension of the CVD-W emitter, and (2) a T-111 choke which would be joined to the T-111 emitter. In the first case, the emitter-choke interface was assumed to be at 1600°C and in the second case, at 1500°C. The choke surrounds the heat pipe which operates at 1000°K (727°C).

The lengths of 0.030" thick W and T-111 chokes required to drop the temperature at the choke-seal interface to 1000°C were 1.28" and 0.97", respectively. The ID of the choke cylinder was 0.580", compared to the emitter ID of 0.520", to eliminate thermionic emission from the choke.

Review of available diffusion information indicated the transition weld joint between Nb-1Zr at the bottom of the GGA seal and W or Ta chokes should be located such that its operating temperature would be limited to assure long life without degradation. A 1000°C maximum temperature at this joint would assure that leakage or failure would not occur as a result of Kirkendall void formation.

The temperature limitation noted also maintains the Nb-1Zr to Alumina insulator at a comparable level. The GGA seal has demonstrated satisfactory life at 1000°C to assure the 10, 000 hr design performance goal of the diode.

In addition to enhancing the confidence of seal integrity by operating at 1000°C, such operation would also permit direct attachment of the Nb-1Zr to SS transition joint to the cold end of the seal. An expected temperature drop across the seal of greater than 200 °C would bring the cold end of the seal down to less than 800°C, the nominal allowable operating temperature of the transition piece.

A change was made in the method of maintaining the desired spacing between the heat pipe and emitter. It was originally planned to use a zirconia ring-rhenium wire separator arrangement, similar to the one developed by TECO, at each end of the emitter. However, it was later learned from JPL that the rhenium wire would not be compatible with the emitter. Therefore, the rhenium wire was eliminated and zirconia rings alone would be used to obtain the desired heat pipe-emitter separation.

In the modified design, the surface of the spacer in contact with the emitter was crowned to avoid a sharp edge contact between the spacer and emitter. The spacer was made up of four segments to accommodate differential thermal expansions between the heat pipe and separator.

As will be seen in the discussion of Task 2, a sump region at the bottom of the heat pipe was required. The additional length required to the T-111 emitter assembly was accomodated by the relatively simple operation of welding a T-111 tube of proper dimensions to the existing assembly.

IV.A.2. Task 1 - Analytical Performance Predictions

The diode module analysis was accomplished primarily through use of DIODE, a Westinghouse digital computer code which solves and integrates the diode performance functions for a specified geometry, operating condition, and J-V characteristics. The output format of the code is both tabular and graphical.

The original version of the code was written for the in-house parametric scoping studies of thermionic reactors employing externally fueled, double-ended diodes. It was therefore limited to the reactor module geometric configuration and diode performance characteristics. The code was subsequently modified to calculate the performance of the experimental diode module configuration.

The DIODE code was modified to calculate diode performance characteristics more accurately and yield more explicit output data. For example, an improved description of experimentally measured or calculated J-V characteristics is used as input to this new version of DIODE. Typical data applicable to the experimental module was assembled from TECO(4) reports and SIMCON(5) calculations.

The DIODE program changes included improving the logic and refining the calculational procedures to yield a more accurate and explicit analysis. For example, the radiant heat transfer rate can be input as a constant or the code will calculate a value for this parameter as a function of the emitter and collector temperatures. This calculation uses SIMCON data for a W-Mo diode. Performance data bracketing the design operating temperatures of the CVD-W module were generated using DIODE. The graphical output from the code for this module operating at emitter, collector and cesium reservoic temperatures of 2000, 1000 and 610°K, respectively, is presented in Figure 12 (all dimensions are given in inches). Voltage (V) - current density (J) data at the operating conditions were obtained from SIMCON. The J-V data curve was input to the DIODE as a 3-leg linear approximation. The magnitude of the error inherent in the approximation should be of minor importance since the diode would be operating mainly between 2 and 10 amps/cm^2,

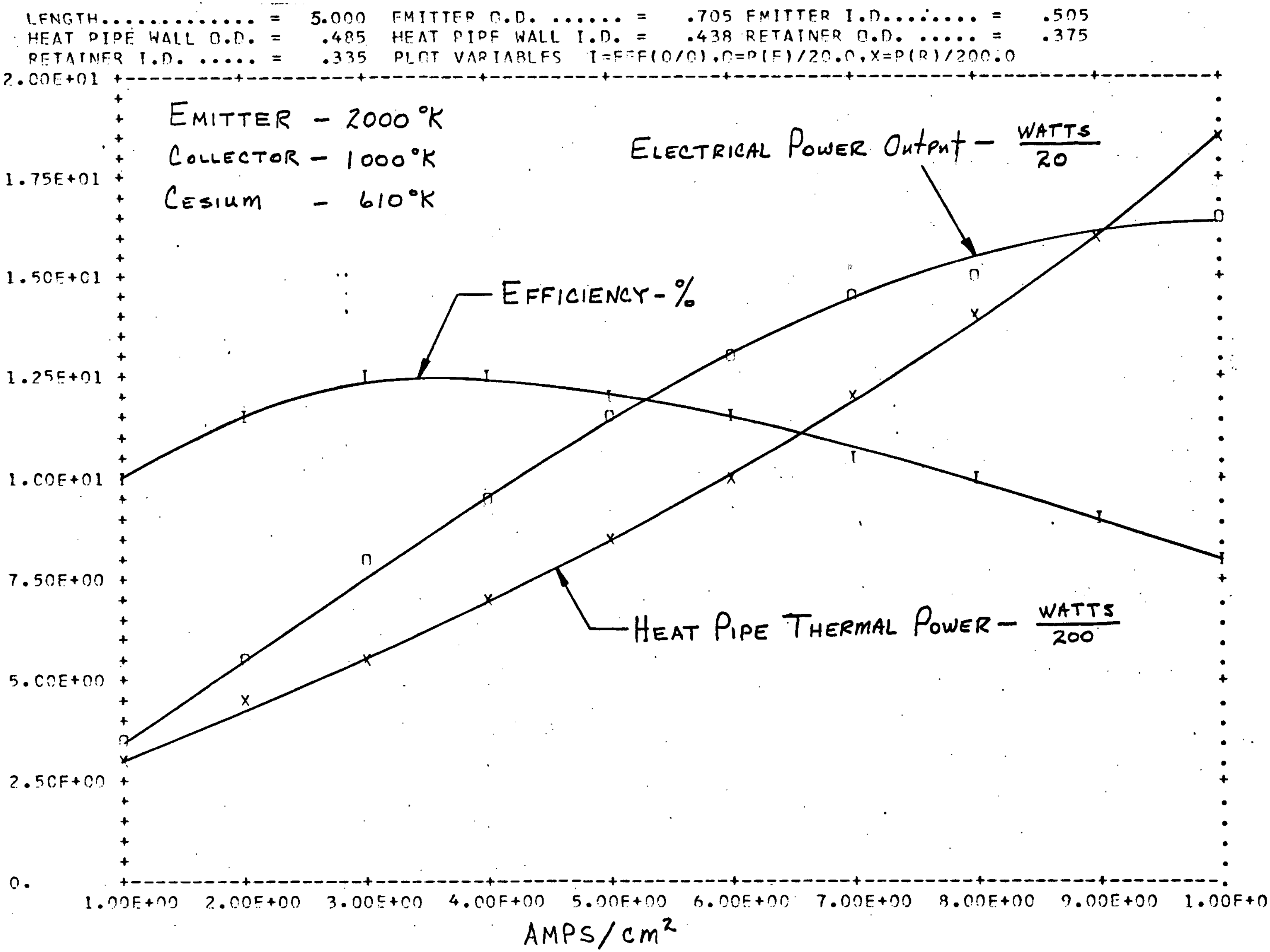


Figure 12. DIODE Output Data for CVD-W Module

where the linear approximation is fairly accurate.

A magnetic tape copy of the DEXTER [(6)] diode analysis code was obtained from its author, C. Sawyer (JPL). DEXTER was successfully compiled and the sample problem executed on the CDC-6600. This code was to be used in conjunction with DIODE to perform test predictions and analyses.

IV.A.3 Task 2 - Fabrication

The diode fabrication effort involved fabricating or procuring the several diode components: emitter, collector, seals, flanges, bellows, etc., and then assembling these into a complete diode. All components were fabricated and assembled, except for the collector/heat pipe. This item is treated separately in Section IV. B.

As part of the Initial Program, materials were obtained for the high temperature brazing of high purity ceramic to metals. Three furnaces with different volume, vacuum and temperature capabilities were used in the brazing test operation. Experience as to proper firing sequence, vacuum condition, top temperature, holding time and cooling rate for the brazing compounds, were gained and evaluated. A sample active metal seal of Coors AD998 alumina to Nb-1Zr at 1500°C is shown in Figure 13; the brazing material was Ti-V-Zr in 1:1:2 ratio. The sample was leak tight at all four brazed joints and survived a simple temperature cycle to 1100°C. A full size "hat" seal similar to the experimental seal shown in Figure 13 was fabricated, thermal cycled, and leak tested. The metal to alumina joint involves balanced brazing to Nb-1Zr flexure pieces.

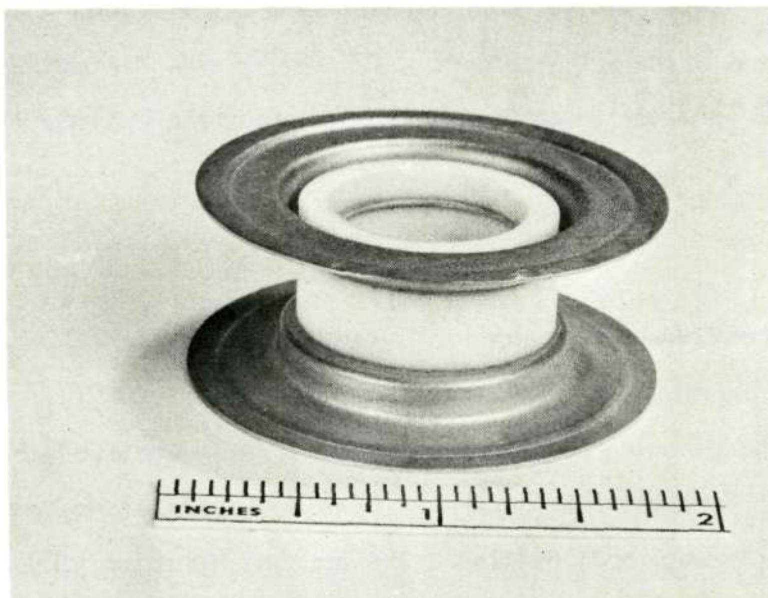


Figure 13. Active Metal Brazed Seal (Nb-1Zr to Alumina)

Aside from the above seal and heat pipe development programs, no further fabrication effort was expended during the Initial Program. The major portion of the Task 2 effort dealt with the Revised Design.

The upper end support structure pieces for the T-111 diode were fabricated. These included the T-111 thermal choke, the modified emitter assembly, modified heat pipe flange and a two inch long transition piece obtained from the Whittaker Corporation.* All pieces were made compatable for use with the GGA ceramic seal. High purity yttria stabilized zirconia disks (0.200" thick, 5/8" diameter) were received** for use as the insulator in the split bushing arrangement.

The T-111 thermal choke was EB welded to the emitter end and checked to verify that it was leak-tight. This assembly, including the emitter proper was finish machined to a mirror finish using a diamond honing procedure. This was done to achieve tight dimensional control of the gap between the emitter and collector as well as to facilitate module assembly. The emitter assembly was out-gassed prior to welding to the seal and transition joint.

The fabrication of the T-111 emitter for use in the Revised Program was completed. Figure 14 shows the assembled hardware, with the seal and transition joint welded in place. The assembly exhibitied no structural faults and was successfully leak checked.

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* The procedure-brazing or use of a transition joint - to join the Nb-1Zr ceramic insulator seal to the stainless steel bellows was investigated. From a reliability standpoint, the latter, was preferred. Transition joints of Nb-1Zr to 316 stainless steel were obtained from the Whitaker Corporation, Nuclear Metals Division, West Concord, Mass.

** Don Ernst of TECO is gratefully acknowledged for his kindness and cooperation in obtaining these pieces.

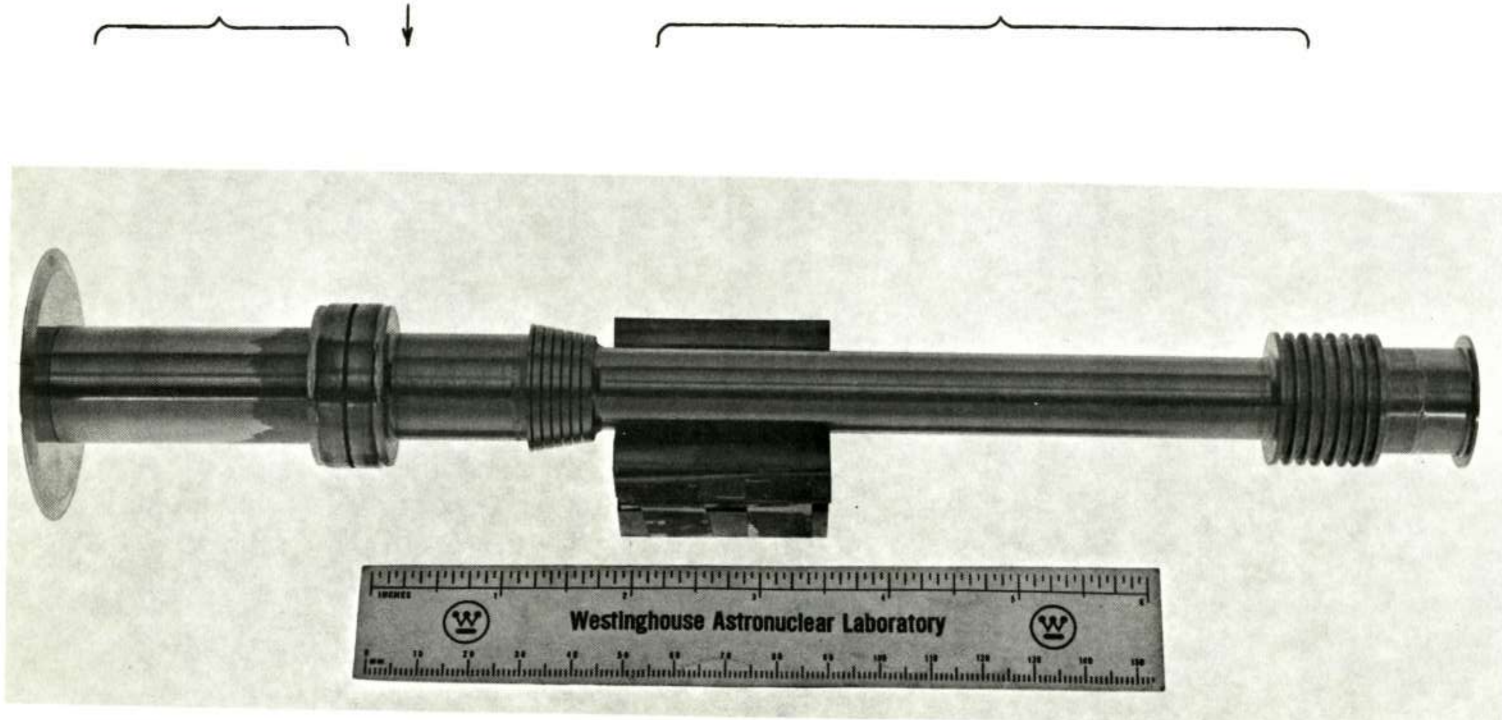

Figure 14. T-111 Emitter Assembly

IV.A.4 Task 3 - Testing

Although actual diode testing was precluded by heat pipe diffuculties, several items in this Task were initiated. The Diode Test Rig was modified to meet the program requirements and a detailed Test Plan was written.

The diode test rig was modified to accommodate the revised diode design. The original test chamber had two bolted joints with gold "O" ring seals to prevent cesium leakage into the chamber. Since these could give way under operating conditions, a modified test rig heat pipe flange was welded directly to the bellows. The diode test facility was also modified to employ the integral cesium supply attached to the diode. With this, the diode becomes a self-contained unit.

In fulfillment of contract milestone (a) (3) (A), the Test Plan Document [7] was developed and submitted to JPL for approval. The Test Plan defines the procedure to test the thermionic diode designed under Task 1 and fabricated under Task 2 of this subcontract. The first step in the Test Plan starts after the assembled diode is installed in the test rig. The test is divided into two sub-groups: the testing of the vacuum and electrical integrities of the diode and test systems (Testing) and the tests of the diode performance (Experimental).

The Diode Test Facility (Test Rig) was designed, fabricated, assembled, and checked out in anticipation of the Task 3 and 4 Testing and Experimental efforts. The details of the Test Rig components, Test Plan, and discussion of the test instrumentation appear in Reference 7.

The diode tests were to be conducted using the existing test rig shown in Figures 15, 16 and 17. An engineering drawing of this assembly is given in Figure 18*. The components of the test rig are described in Table 2. The heater used to simulate the thermionic reactor, the

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*This drawing does not include the modified integral cesium reservoir unit or the heat pipe calorimeter which is shown in Figure 7.

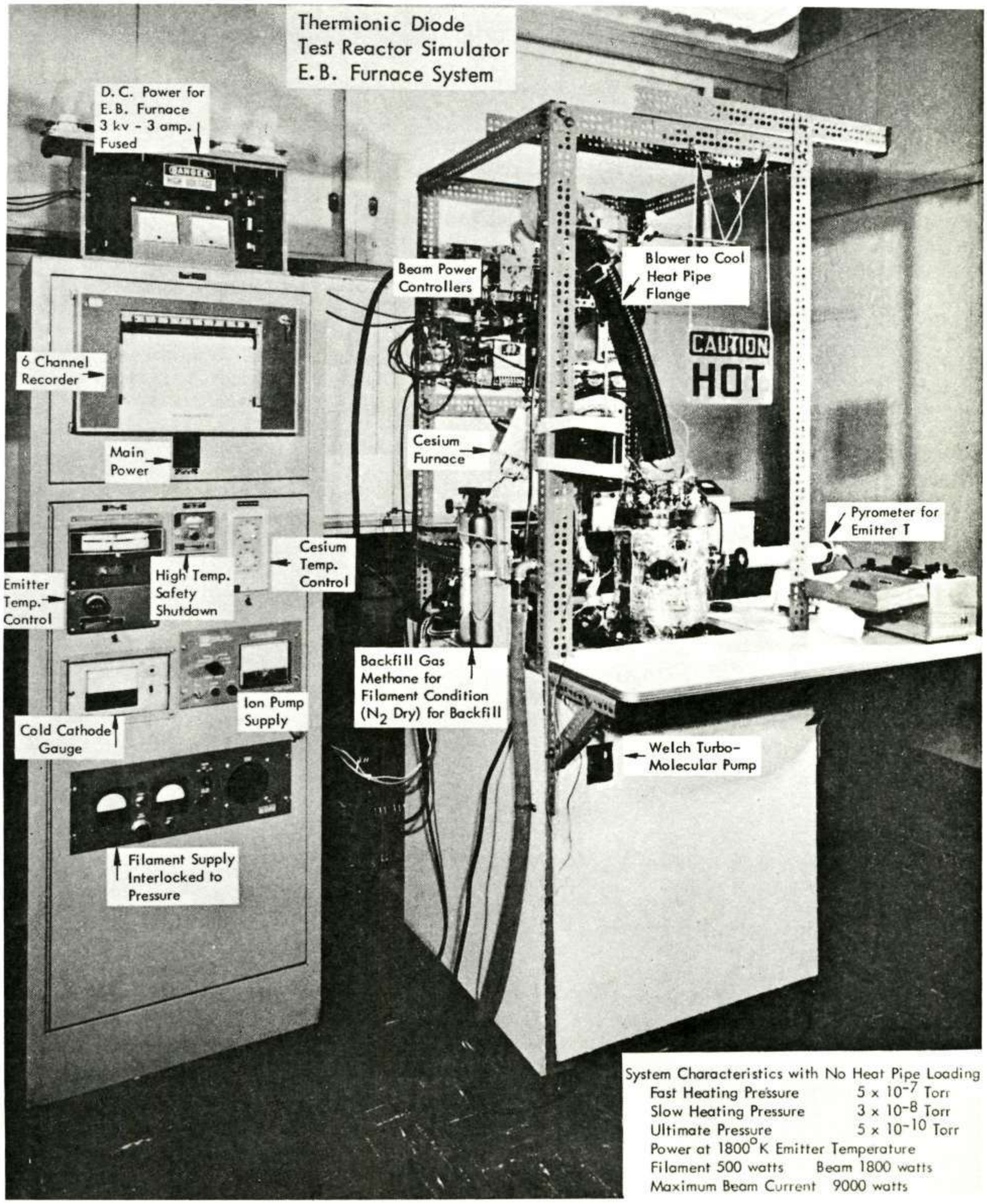

Figure 15. Test Rig

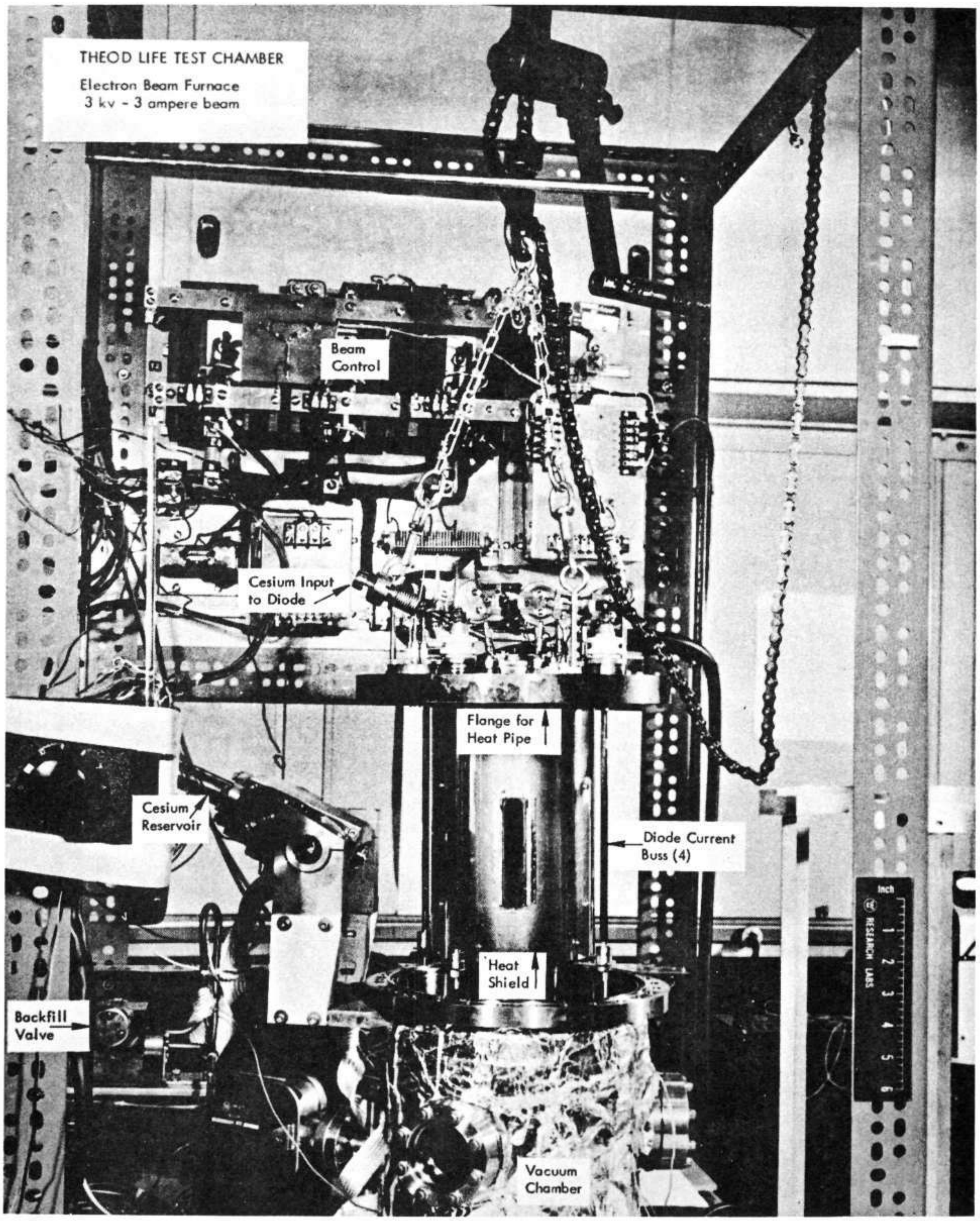

Figure 16. Test Rig (Details)

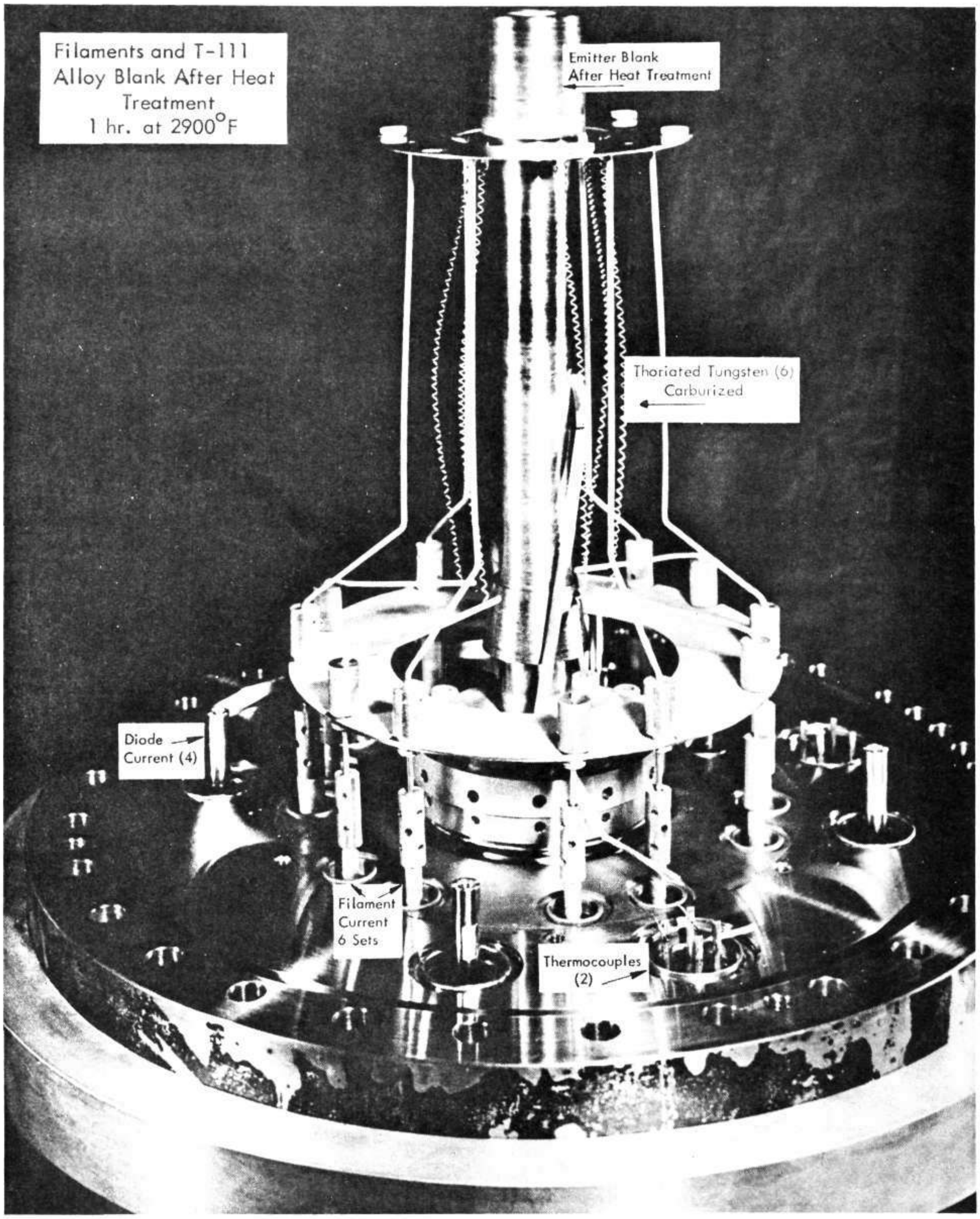

Figure 17. Test Rig (Electrical)

Calorimeter

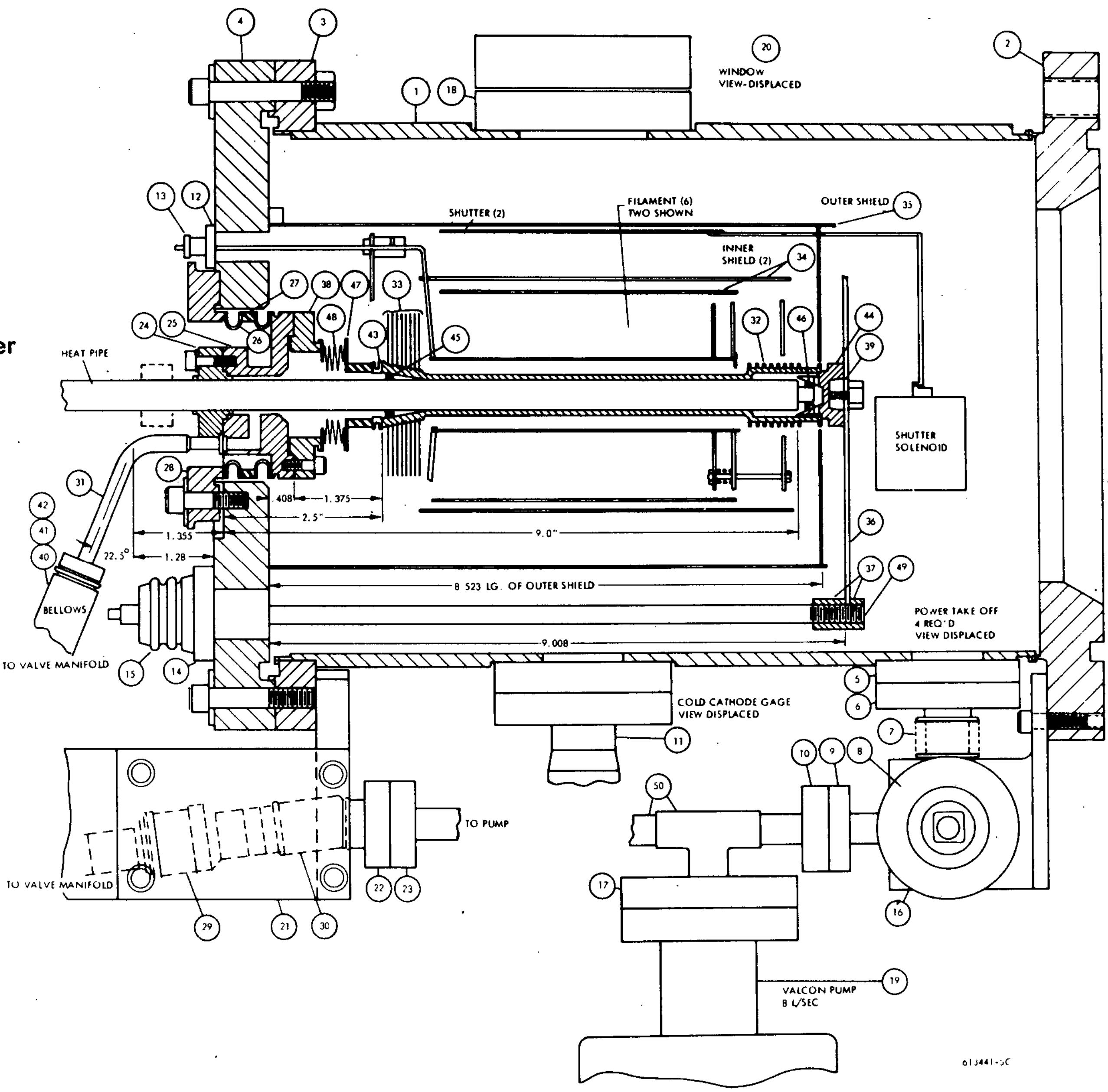

Figure 18. Test Rig Assembly

TABLE 2. Components of the Test Rig

1.	Outer Envelope 6" SS Pipe
2.	Bottom Flange of Envelope
3.	Upper Flange of Envelope
4.	Top Flange
5.	Pump
6.	Flang to Valve
7.	Adapter Bellows (SS-1101192R) for Valve
8.	Valve
9.	Flange (Dwg. 11-667 Item 7)
10.	Flange (Dwg. 11-667 Item 2)
11.	Cold Cathode Gauge Hrc 524-2
12.	Stand Off
13.	U.S. Stone Ware Feed Thru B-27-1
14.	Stand Off
15.	Power Feed Thru U.S.S. No. 1-2-1C
16.	Valve Bkt.
17.	Flange for Cold Cathode Gauge
18.	Flange For Window
19.	Valcon Pump 8 L/S Model No. 911-5000
20.	Ultec Viewport Model No. 80-432
21.	Bracket for Valve Manifold
22.	Flange to Fit Elbow of Item 31 (Item 2 Dwg. AMS 11-667)
23.	Flange to Match Item 34 (Item 7 Dwg. AMS 11-667)
24.	Heat Pipe Flange
25	Cesium Inlet Flange
26.	Kovar Spinning (Both Flng. Dia. 2.625) Dwg. AMS 11-2668
27.	Ceramic Ring
28.	Heat Pipe Flange (at insulator)
29.	Ceramaseal Terminal (Ceramic) No. 805B0106-2
30.	SS Bellows 15 Convl 1 5/8 Lg., 1/2 I.D. x 3/4 O.D.
31.	Cesium Inlet Tube
32.	Emitter
33.	Fins
34.	Inner Shield Moly
35.	Outer Shield SS
36.	Power Take Off Plate Moly
37.	Nuts for Item 58
38.	Emitter Flange SS
39.	Nickel Adapter for Power Take Off Phase III
40.	Adapter To Bellows (Cesium Inlet)
41.	Bellows Ring
42.	Bellows For Cesium Inlet Tube
43.	Transition From Emitter to Ceramic
44.	Emitter Cap
45.	H.P. Insulator
46.	H.P. Insulator (Bottom)
47.	Kovar Sheet from Ceramic to Bellows
48.	Bellows
49.	Power Leads
50.	Valve Tubing Assembly

heat pipe calorimeter, the cesium supply, the main pump, and the safety controls are discussed in Reference 7.

IV. A. 5 Task 4 - Experimental

The diode experiment portion of the program could not be performed because of the aforementioned difficulties in developing the high performance heat pipe.

IV. B. Heat Pipe

As discussed previously, there were variations in the heat pipe designs employed in the Initial and Revised Programs. The differences between these pipes involved annular gap size, wall thickness, use of wick restrainer or rigid swaged wicks, sump dimensions, and use of a Zr getter foil. The technical discussion of these pipes is given below and includes treatment of design details, performance analysis, fabrication procedures, heat pipe test results, the problems encountered and possible solutions. Also covered in this section are the heat pipe tests performed at LASL.

IV. B. 1 Initial Design

A thermionic heat pipe capability analysis was performed, considering both Na and K as the working fluids. It was decided [8] to increase the annular liquid metal gap in the heterogeneous wick heat pipe from the early design value of 0.009" to 0.027" to reduce the I^2R loss in the collector. This would be accomplished by using stainless steel heat pipe tubing having an ID of 0.438" rather than the initial 0.402", maintaining the tube OD of 0.485". The heat transport capability of the working fluids are shown in Figure 19.

Figure 19 indicates better expected performance using K, although Na has sufficient heat transfer capabilities to meet contract requirements. With the approval of JPL, Na was selected as the working fluid primarily because of prior WANL experience with Na handling and fabrication of Na charged heat pipes.

The first high power (Figure 9) collector/heat pipe employing a wick restrainer* (HP1) was processed and tested. This heat pipe was charged with 12.0 grams of sodium which gave a 0.5 gram excess at the selected operating temperature (700°C).

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*Wick swaged to restrainer and resistance welded.

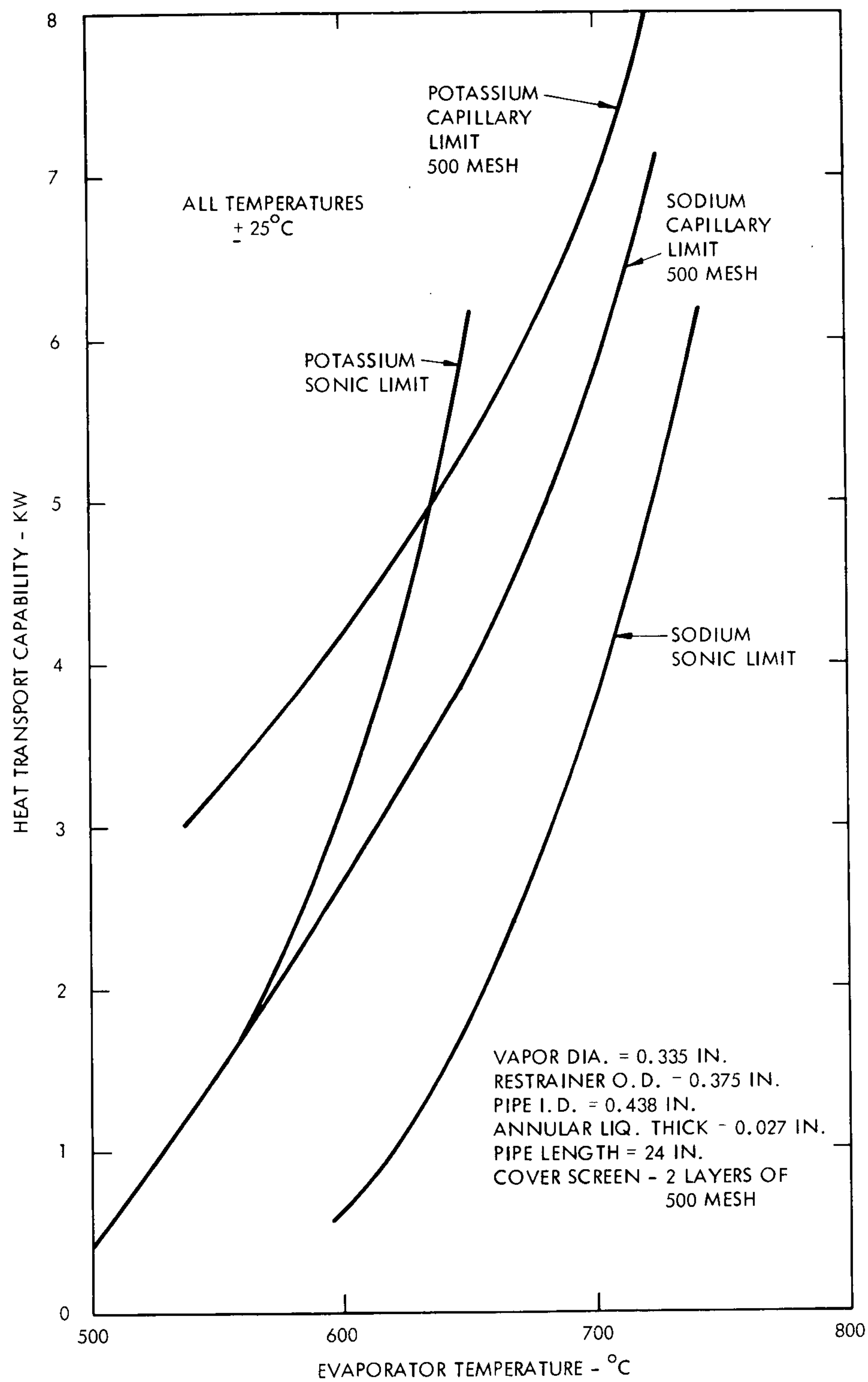

Figure 19. Heat Transport of Heat Pipe Working Fluids as a Function of Collector Temperature

HP1 was instrumented with 11 thermocouples, as illustrated in Figure 20, and covered end-to-end with a 1" thick layer of fiberfrax insulation. Its initial checkout operation using RF induction heating, was in the vertical position, evaporator down. These low power check-out tests were economic, quick determinations of heat pipe operability, and were made prior to the full power testing. Initially, temperatures at TC No. 1 location read high, and returned to a flat profile whenever the pipe was tapped. After operating in this fashion for 6 days (with TC No. 1 cycling), the temperature profile flattened out and excursions of TC No. 1 ceased. Subsequent shutdown and restart found the thermal instability at TC No. 1 location to return. X-rays revealed the wick mesh to be continuous and in proper position.

The heat pipe was retested in the horizontal position, and resulted in a very stable, isothermal temperature profile end-to-end of 700°C. Operating vertical, evaporator up, also resulted in an isothermal profile, with TC No. 1 again reading 20 to 60° above the pipe temperature.

Test information from HP1 indicated temperature abnormalities at the heat pipe extremities when it was operated evaporator up or down with respect to gravity. Horizontal operation was acceptable. Open annulus heat pipes are particularly susceptible to small gas bubbles. Any noncondensible gas, introduced during pipe processing or test operation, would traverse the pipe in the annular zone and block off fluid in the evaporation region or prevent wicking against gravity. Since this pipe was processed at 10^{-6} torr, uncommon sources of gas contamination were investigated.

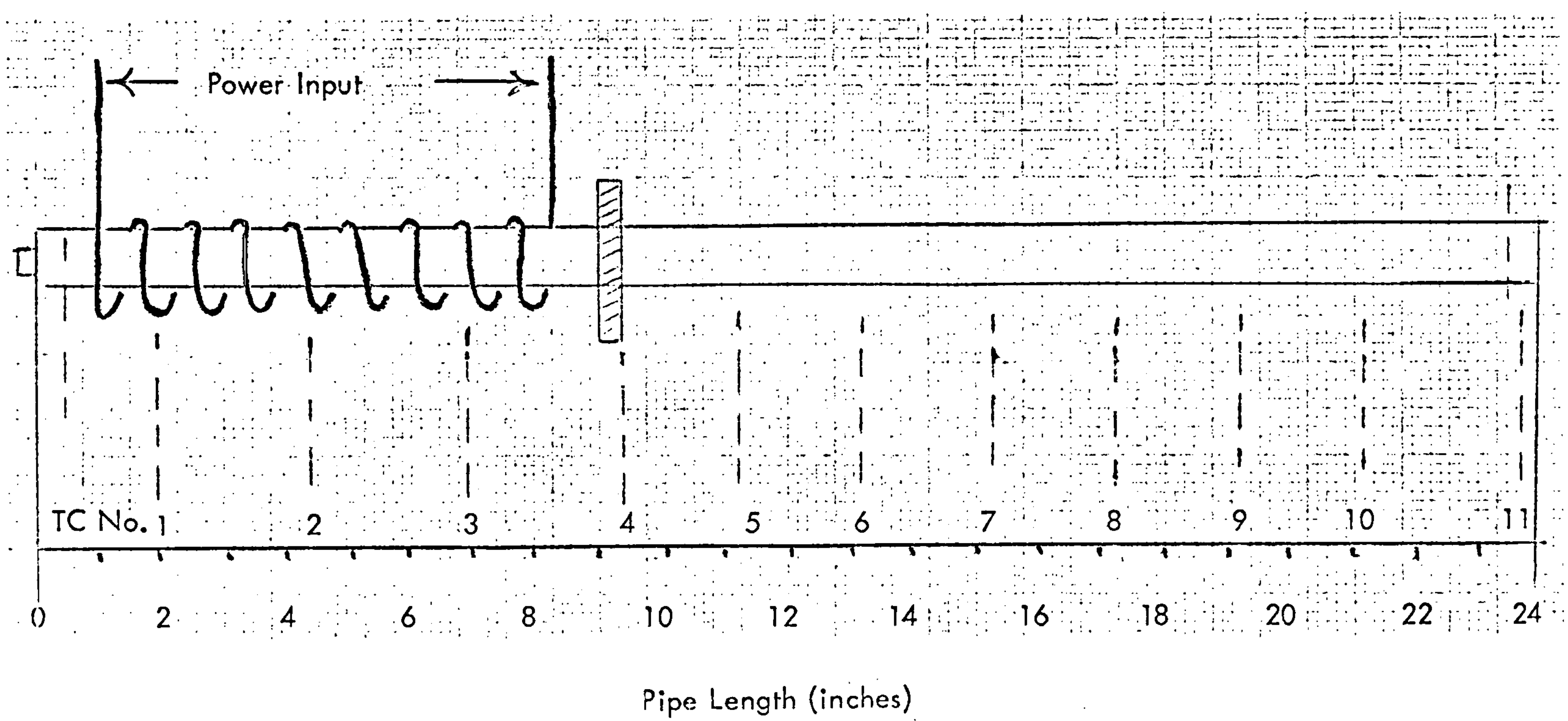

Figure 20. High Power Geometry Thermionic Heat Pipe Instrumented and Tested in the Vertical Position, Heater Down (Unit Covered by 1" Thick Layer of Fibrefrax Insulation End-to-End).

In the sodium loading technique employed for this pipe, the outgassed (600°C for 9 hours at 10^{-6} torr) heat pipe was sodium charged (solid sodium at ambient, 16 psia argon) under monitored (oxygen, moisture)argon. The EB weld seal was made at 10^{-5} torr pressure without prior heating to remove absorbed argon. Calculations, following S. Dushman,[9] showed that if the large surface area in the thermionic heat pipe absorbed a monolayer of argon during processing, sufficient gas would be released upon heating the sealed heat pipe to affect its operation. An experiment was devised to test this premise.

An empty tube (24 inches long by 0.5 inches diameter) with an ion gauge tube fixed in one end was placed in the vacuum box and the box was evacuated. The ion tube reading was approximately one order of magnitude higher pressure (10^{-5} torr) than the box pressure (10^{-6} torr). A vacuum manipulator was used to insert the end cap. The pipe pressure rose slightly during insertion of the end cap, but rapidly returned to 10^{-5} torr. A second tube containing 4-turns of 200 mesh screen was outgassed at 500°C in the box (10^{-6} torr) and the box was backfilled with argon. The second tube was placed before the EB weld gun, the box evacuated to 10^{-6} torr, and the end cap placed into the heat pipe using the vacuum manipulator. After EB welding the end cap in place, the ion gauge tube was activated. It would not start. This indicated a large release of gas by the EB weld process.

Since it was believed that the inability of the ion gauge tube to start might have been due to its own outgassing, the test was repeated with a cold cathode vacuum gauge. Following the EB weld seal on the pipe end cap, the tube internal pressure was in excess of 100 microns at room temperature. Inserting half of the tube length in liquid nitrogen lowered the pressure only slightly, indicating that the gas contaminant was not an easily condensed gas such as water vapor, CO_2 or CH_4. A 1/64 inch hole was subsequently drilled in the end plug and nominal chamber pressure was attained inside the pipe. Subsequent EB weld resealing of the hole, however, again generated an internal pressure of 100 microns. This final reading was obtained during the EB weld seal while the chamber was at 10^{-6} torr; thus, external leaks to the pipe system could not be considered.

Since the previous tests illustrated the presence of an internal gas pressure in the heat pipe following a vacuum EB weld seal on the end cap, subsequent heat pipes were processed with a valve (Nupro bellows seal vacuum valve) on one end to facilitate non-condensible gas removal by a vacuum pump following sodium charging. The valves were later removed by a weld/pinchoff technique.

A 0.5 inch O. D. by 24 inch long heat pipe (HP 2) was loaded, end-cap welded, evacuated and sealed in the manner described above to obviate the non-condensible gas problem. HP 2 employed a swaged wick of five turns of 500 mesh screen forming a rigid tube, thus eliminating the need for a wick restrainer.

RF induction heating was initially used as the heat input mechanism for the heat pipe check-out tests. Such tests were quick, economical, required a minimum of auxiliary equipment and were successfully employed in prior heat pipe checkout operation. However, these tests now showed that some anomalies were appearing in the operation of the heat pipe. They took the form of a hot spot in the evaporator at power levels much below where one would ordinarily expect to observe such conditions. Thus, the technique of RF coil induction heating of the heat pipes was reconsidered. The skin depth of induced current for the geometry employed was calculated to be 0.032 inches (i.e., depth at which current equals 33% of surface current). Since the pipe wall thickness was 0.035 inches, it was thought that the magnetic field could be penetrating the heat pipe wall and affecting the sodium distribution. The moving field (collapsing at 450 KC) coupled with the induced electric current in the sodium could act to force (pump) the sodium from the wick. Open annulus pipes would be more susceptable to such forces than similar pipes having homogeneous wicks, due to their lack of wick structure near the pipe wall (i.e., surfaces to retain sodium). This analysis was reviewed with RF heating specialists at the Westinghouse Reasearch Laboratories, and a 0.100 inch wall heat pipe was recommended for use in RF testing of this nature.

HP 2 was later inserted in a 1/2 inch hole in a stainless steel heater block, and was flanked in adjoining holes in the heater block by two 3,000 watt (e) Watlow firerod heaters and two 500 watt (e) Watlow guard heaters. Orientation was vertical, evaporator down. Full calorimeter instrumentation tests showed this heat pipe to transmit over 2,000 watts(t) at 730°C. The test was terminated due to heater temperature limits being exceeded. No pipe operating anomalies were observed.

A heat pipe (HP 3) having the revised (thickened wall) design was fabricated. The internal structure (pipe I. D., swaged 500 mesh wick, and open annulus for sodium return) of this pipe was the same as HP 2. The outside dimensions, however, were different, since the heat pipe wall now had a basic O. D. of 0.625 inch to have a 0.095 inch wall thickness.

All components of the heat pipe were fabricated and assembled. The pipe was out-gassed at 750°C and 10^{-6} torr, sodium charged, and wick wetted at 830°C for 72 hours in a 2×10^{-5} torr retort. It was planned to perform full instrumentation checkout on the RF induction heating coil unit before the 0.095 inch wall was machined to 0.030 inch in the evaporator region. The testing with the 0.095 inch wall was expected to eliminate the previous problems noted with RF heating.

HP 3 was checkout tested (thermocouples were attached axially at two-inch intervals) using a low power heater at one end (0-400) watts (e)), and complete insulation end-to-end. These checkouts verify heat pipe operation by demonstrating low power heat transfer while exhibiting characteristic heat pipe temperature profiles. The heat pipe was accepted, exhibiting an isothermal profile (while horizontal) of 600°C. RF testing of the heat pipe resulted in a hot spot appearing in the evaporator. At this time, it was assumed that the skin effect was still perturbing pipe operation due to its open annulus structure.

The heat pipe was, therefore, instrumented for full power checkout with a resistance heater block and a water cooled/gas annulus variable load calorimeter. A 6,000 watt (e) resistance heater block was clamped to the evaporator end of the heat pipe with mild steel shims. Heat pipe startup characteristics in the vertical position (heater down) were normal until approximately

700 watts (t) were transmitted with the evaporator zone at 600°C. At these conditions (reproducible), the heat pipe evaporator exhibitied hot spots due to dry wicking (loss of sodium from the annulus in the heat input zone).

Operation of this heat pipe was such that several hypotheses were advanced concerning poor operating behavior. Of the hypotheses advanced, that of the sodium fill appeared most critical. The volume of sodium required to fill the annulus, wick, and sump at 740°C was calculated as:

Annulus	16.30 cc
Wick (62% porous)	3.21 cc
Sump (0.375" deep)	0.64 cc
	20.15 cc

However, the sodium charged to just fill this volume at 740°C (15.5 gms at 0.775 gm/cc) was not adequate to fill the wick plus annulus at 500°C. Ideally, the wick plus annulus should be filled from room temperature to operating temperature to prevent voids and gaps in the annulus. Hence, a sump allotment of Na must be added to the pipe. Overfilling would cause problems in sodium superheat boiling and chugging.

Since the sodium inventory distribution is not fully known during heat pipe operation, a larger sump was required to insure adequate sodium during pipe startup and operation to temperature. Calculation showed that if a 2-inch sump is permitted for 740°C operation, then just enough sodium to saturate the wick and annulus at 100°C could be charged.

A backup heat pipe (HP 4) was fitted with the flange from HP 3 and was processed in the following manner. All fittings to the titrator system were welded and helium leak checked; the pipe, valve train, and titrator reservoir were outgassed until heating any one spot to an orange glow failed to produce any rise on the vacuum pump pressure reading (10^{-6} torr range). Sodium was loaded under helium (at 1.8 ppm oxygen-9 ppm moisture) in the vacuum/glove box. Wick wetting of HP 4 was accomplished at 850°C for 90 hours in a vacuum retort.

Because of the hot spot noted in the RF testing of the first thick walled heat pipe (HP 3), this form of testing was abandoned in favor of the more controllable heater block approach.

After loading and sealing HP4, it was discovered that a small quantity of Na was frozen in the titration tubing and the pipe was filled with only 17.0 grams of Na, rather than the specified 18.65 grams which was loaded in the titrator. It was feared that the smaller amount of Na might cause start-up difficulties, though once the Na heats up and expands, 17.0 grams is sufficient to fill the annulus, wick, and provide a 0.8" sump.

When the pipe was tested in the heater blocks, a successful start-up was achieved. The pipe operated essentially isothermally, except in the 2" sump region below the heater block, up to almost 700°C, transferring more than 1400 watts(t). At this point, excessive temperatures were noted in the sump region and the test was terminated.

Examination of the heater block indicated that a Watlow heater had slipped out of the block and was supplying heat directly to the sump, causing it to overheat.

IV.B.2. Final Design

Using the JPL Technical Memorandum (Ref. 3) as a guideline, efforts centered on fabrication of a 0.006 inch annular gap Collector/Heat Pipe (HP 5) and a modified calorimeter assembly that would also provide a dry, inert-gas atmosphere to be maintained around that portion of the heat pipe extending outside of the diode test rig.

Before the wick design was finalized (e.g., number of turns of screen, degree of swaging, porosity, etc) an updated analysis of a 0.006 inch annular pipe with a nominal 0.366 inch vapor diameter was carried out to obtain probable heat pipe performance characteristics. It should be noted that the vapor diameter for a fixed annulus is a controlling factor, when the pipe is either sonic velocity or entrainment limited, the heat throughout then being proportional to the vapor area. Figure 21 shows the heat transfer limitations expected of the 0.006 inch annular wicked sodium heat pipe. It can be seen from the figure that at the T/I collector (heat pipe evaporator) operating temperature of 727°C, the heat pipe is limited by entrainment and the maximum attainable heat flow of ~4.7 Kwt is sufficient to meet the requirements of the Collector/Heat Pipe Cooled Diode experiment. As will be discussed later, HP5 did not operate as expected from the analysis, but developed hot spots under nominal load conditions.

For example, as can be seen from Figure 21, liquid pressure drop does not pose a limit for the nominal 0.006 inch annular gap. However, the pressure drop limit would fall, lowering allowable heat flow if the liquid gap size were reduced. Even with the three longitudinal spacer wires in the annular gap above the evaporator region, it is possible that wick eccentricity in the evaporator region might reduce the liquid gap to a size where the pressure drop would limit operation. Perhaps even more significant, solid impurities from the stainless steel could collect in the liquid, obstructing flow and reducing wick melting.

It was desired to fabricate the heat pipe tube and wick from 347 stainless steel. After contacting several vendors, it was determined that 347 stainless steel was not available as an off-the-shelf item in seamless tubing in the required size. An eight-week delivery period was quoted for new orders. However, 321 stainless steel (which is also stabilized) tubing was available. Use of this metal was approved by G. M. Kikin (JPL) and was ordered. Similarly, 304 stainless steel wick material was approved and ordered.

Wick fabrication and parameter evaluation studies were performed. The amount of zirconium foil required for gettering was calculated. Iniaial calculations of the annulus and sump volume versus the sodium volume (required) as a function of temperature were also made. The 0.006 inch annulus pipe would require 6.48 grams of sodium, have a two inch sump at 727°C, and be filled at ambient (with a 0.98 inch sump). Thus, this heat pipe could be two grams underfilled and still have a filled wick and annulus from ambient to operating temperature. Concurrently, to avoid the previously discussed titration filling problem, a sodium distillation apparatus was designed and fabricated, as was an induction heater test rig.

Fabrication and processing of HP5 was completed. This pipe had a 0.495* inch O.D. in the evaporator region with a 0.028 inch wall and 0.625 inch O.D. in the adiabatic region with a

*To be turned to 0.485 inch O.D. prior to final assembly with the experimental T-111 emitter structure.

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Pipe O.D. = 0.5 in., Vapor Diameter = 0.366 in.
Pipe Length = 24 in., Adiabatic Leg = 10 in.
5 Layers of 500 Mesh Swaged Screen

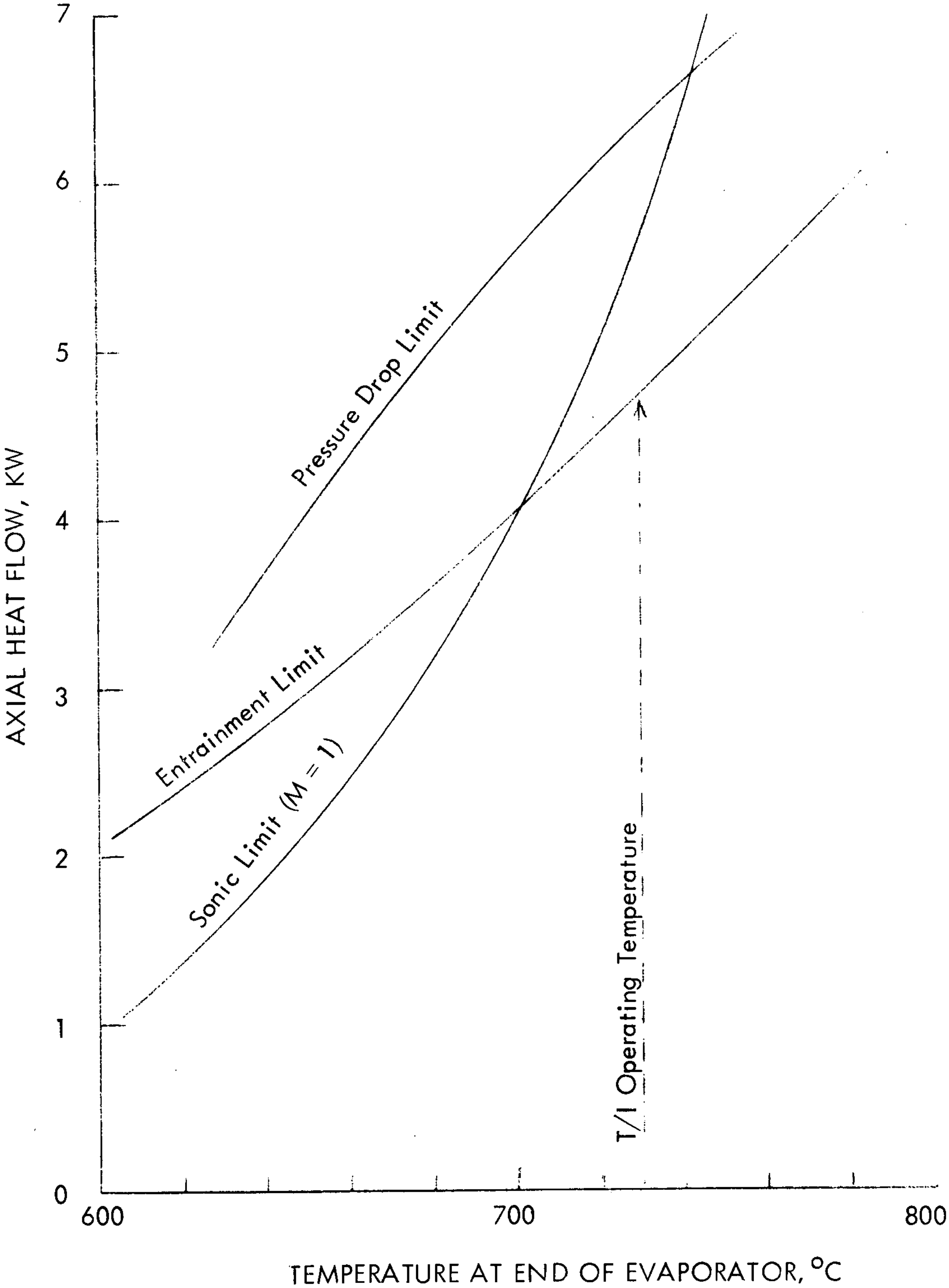

Figure 21. Heat Transfer Limits of 6 Mil Annular Wick Sodium Heat Pipe

0.095 inch wall (to reduce voltage losses). The pipe employed a 500 mesh open annulus (0.006 inch) swaged wick design.

Since re-examination of the previous heat pipe problems indicated that RF heating was not the cause, pipe checkout would be performed using an RF induction heating coil. During the testing, a quartz coil jacket and calorimeter would provide a dry, inert gas environment for the heat pipe.

Detailed calculations were made to ascertain the effect of sodium fill and temperature on the heat pipe sump. If, during operation, the sump height exceeds 2.0 inches and thus extends into the evaporator region of the heat pipe, the pipe would nucleate boil which could destroy the wick. Also, when cooled to ambient, the wick and annulus must still be filled with sodium to prevent void and bubble formation (i.e., potential burnout spots on restart). Figure 22 gives the sump height as a function of the sodium loading and defines the sodium load window.*

The maximum acceptable load of 7.75 grams of sodium (2.0 inch sump at 740°C and a 1.20 inch sump at ambient) could be missed on the low side by 2.25 grams (33%) and the heat pipe would still have a filled annulus. An overload would not be desirable since the sump would then exceed 2.0 inches and boiling (chugging) could result when the sodium level entered the evaporator.

Figure 23 illustrates the upper and lower sump bounds for various sodium loadings as a function of temperature. Since the heat pipe could be required to operate about 740°C for brief periods (i.e., the sump would exceed 2.0 inches if 7.75 grams of sodium were charged), a sodium charge of less than 7.75 grams would be desirable.

The amount of zirconium getter required was calculated to be 2.0 grams or 13 foils, 0.010 inch thick by 0.430 inch O.D. This would be enough zirconium to getter all oxygen in the stainless steel system (ignoring partitioning or the formation of ZrO_2) as Zr ($\underline{O}$) in solution. A sodium charge of 7.40 grams was selected to give a sump height of 1.8 inches at 740°C.

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* These and subsequent sodium load calculations were based on the as-fabricated heat pipe dimensions and wick porosity.

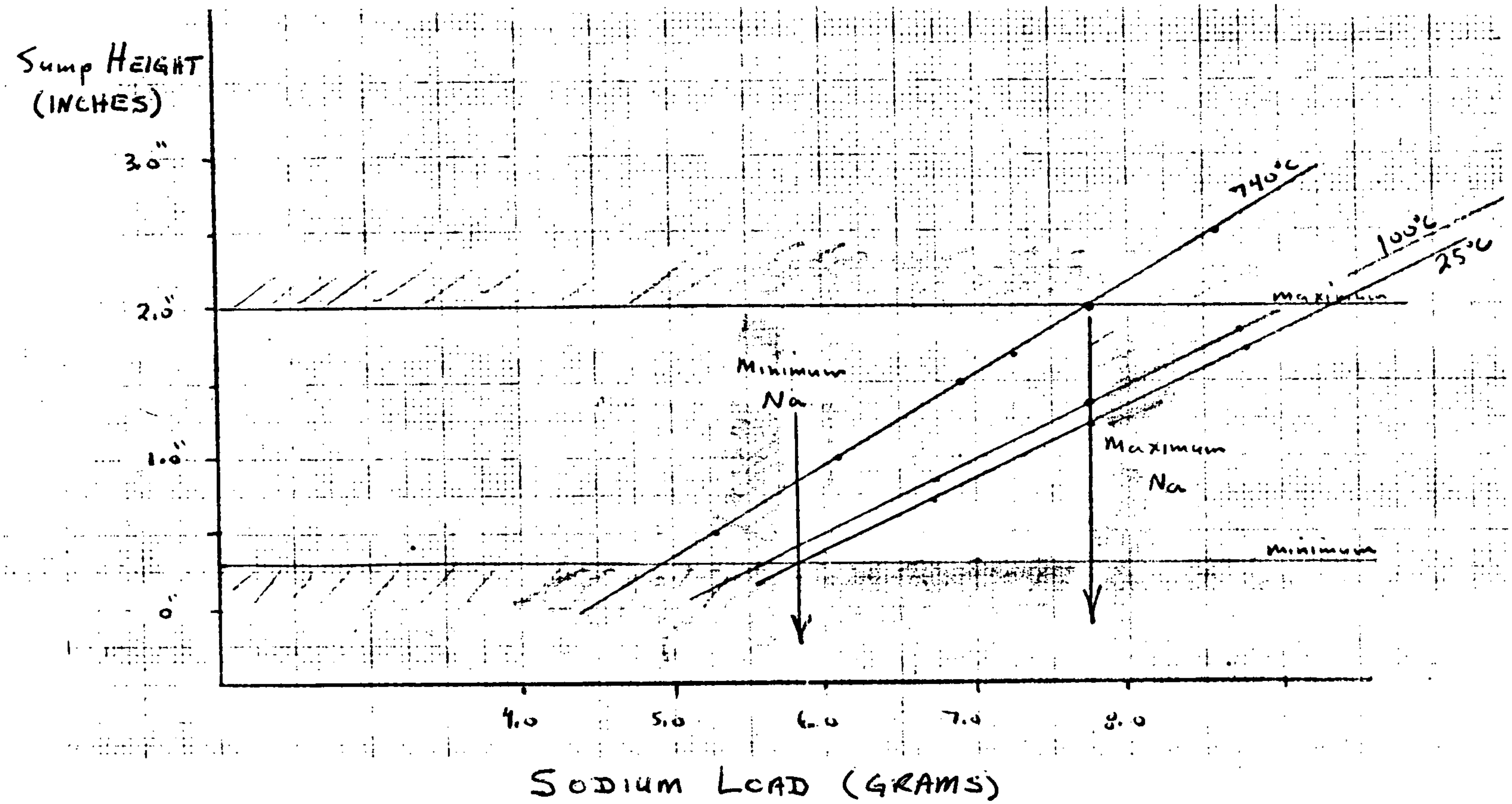

Figure 22. Sodium Load Window

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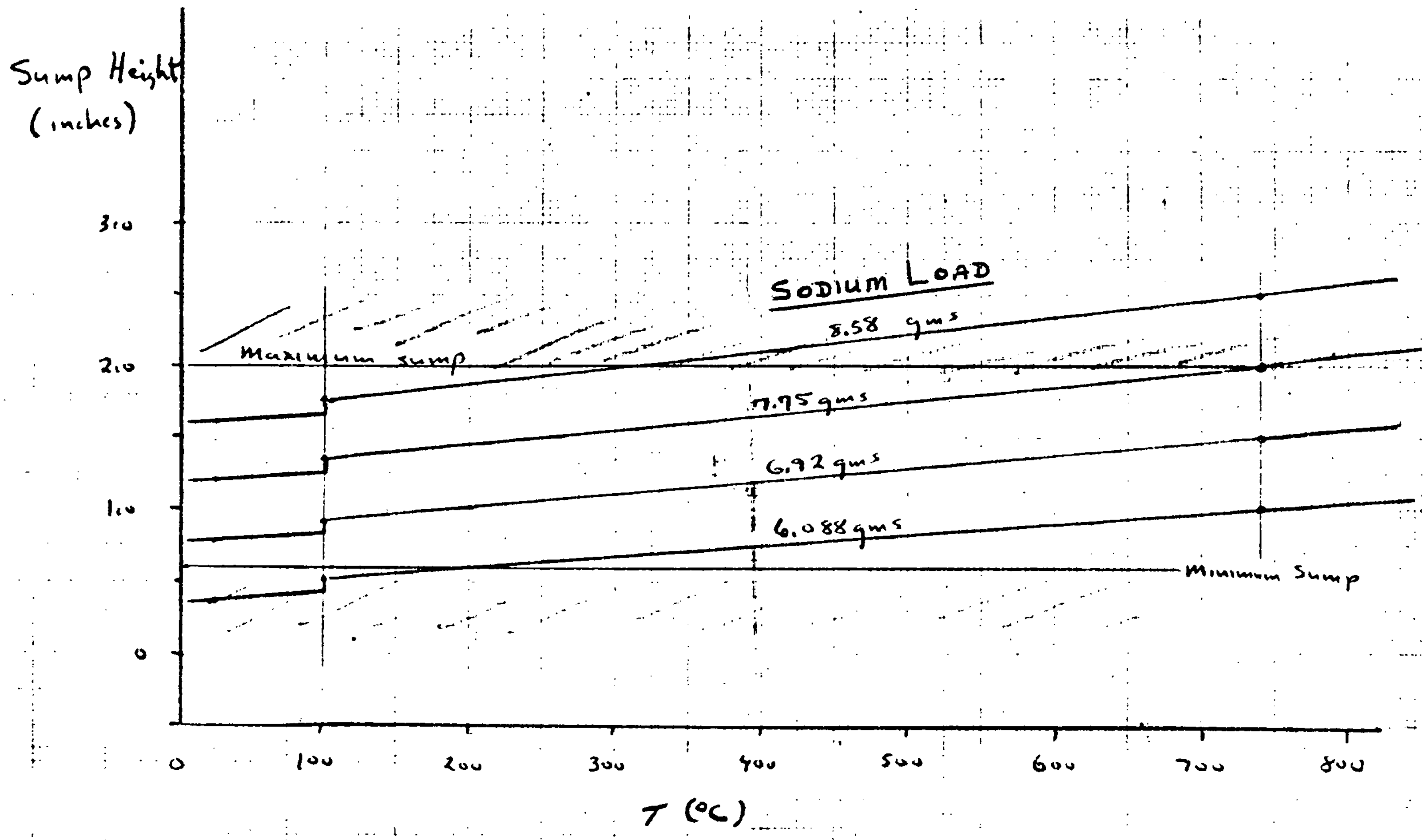

Figure 23. Variation in Sump Height with Sodium Load and Temperature

Fabrication, processing, and testing of HP 5 were carried out. The fabricated casing and wick are shown in Figure 24. Table 3 lists the parameters of the HP 5 hardware.

All casings were dye penetrant inspected for flaws. The 321 SS casings were machined to dimension and the sump plug was welded into position.

The wick (500 mesh 304 SS, twill weave) was rolled to a 50% reduction in thickness, wrapped onto the mild steel mandrel, and swaged to 0.427 inch O. D. This wick was 31% porous (69% dense) and was bubble tested (in menthanol), indicating a pore size of 0.00040 inch radius. A 0.020 inch plug was EB welded into the end of the wick prior to bubble testing.

The heat pipe was welded to a vac-ion pump, distillation pot system (shown in Figure 25). Helium leak checks of all welds and connections were made. The pipe and system were outgassed at 300°C-500°C to 10^{-8} torr for 24 hours. Leak rate was less than 10^{-6} torr/minute.

Figure 26 is a schematic of the sump region of the assembled heat pipe. Figure 27 illustrates the sump geometry and the pinchoff end geometry. Figure 28 shows the zirconium getter foil prior to installation in the sump.

After outgassing, the heat pipe distillation pot and lines were vacuum sealed and installed in a glove box for sodium loading. Box atmosphere of argon contained 1 ppm oxygen and 2 ppm moisture for the sodium loading operation. A load of 7.40 grams of sodium was weighed on a calibrated balance. Tube A (Figure 25) was cut open, the sodium inserted, and then sealed with a TIG weld.

The heat pipe was again outgassed at 300-500°C at 10^{-8} and the sodium pot was outgassed at 100-150°C.* Tube B (Figure 25) was pinched off and welded. The distillation of sodium into the

* Sodium vapor pressure at 100°C is $< 10^{-7}$ torr.

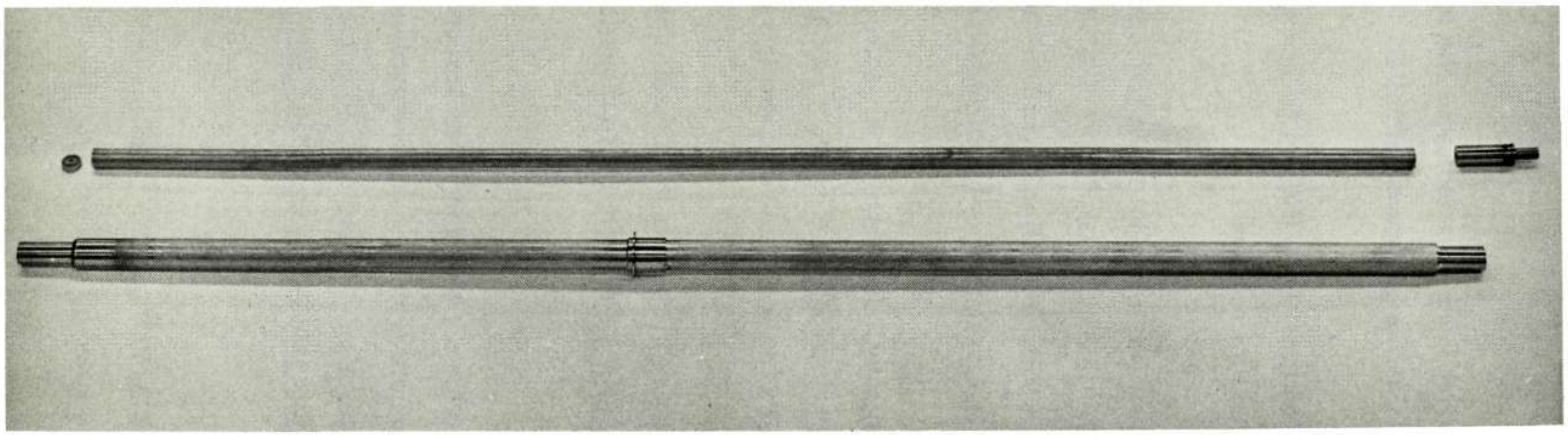

Figure 24. HP 5 Casing and Wick

TABLE 3

THERMIONIC HEAT PIPE HARDWARE PARAMETERS

Casing:	Length	29.438" (Active pipe)
	OD	0.625"
	Wall	0.095"
	ID	0.439" (measured)
Wick:	Length	28.937"
	(Wick attached at one end only -- floating in sump region)	
	OD	0.427"
	Gap	0.006" ($\pm$ 0.0015")
	ID	0.409"
	Thickness	0.009"
	Density	69%
	Pore Size (radius)	0.00040" (bubble test)
	Spacer Wires	0.0045" OD
	Located	Sump, condenser, axial
	Number	3 at 120° angle
Getter:	Material	Zirconium foil
	Weight	1.7205 gms
	Dimensions	0.430" OD x 0.130" high
Sodium:	Weight	7.4 gms
	Sump height at 740°C	1.8" calculated
	Sump height at 25°C	1.1" calculated

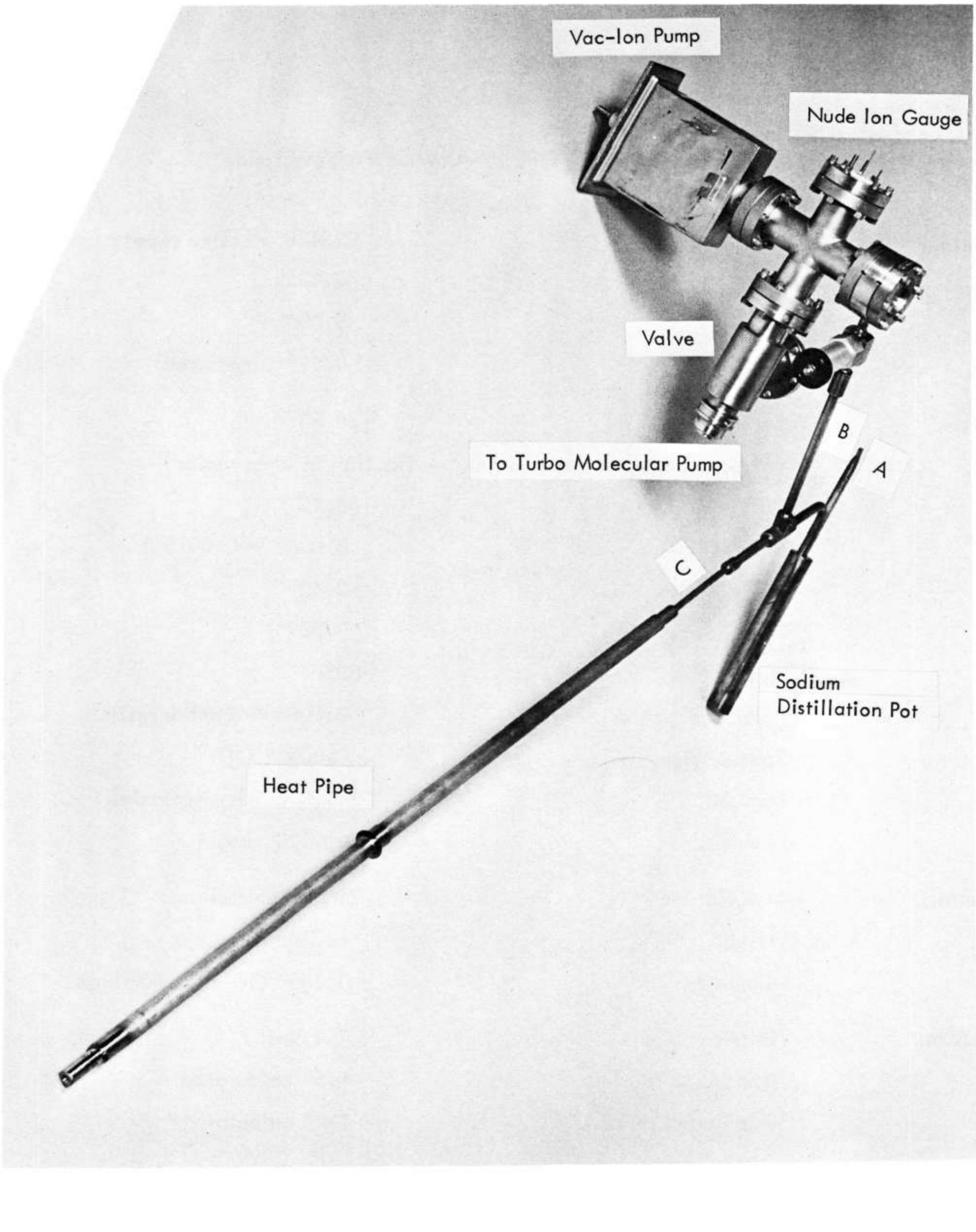

Figure 25. Sodium Distillation System

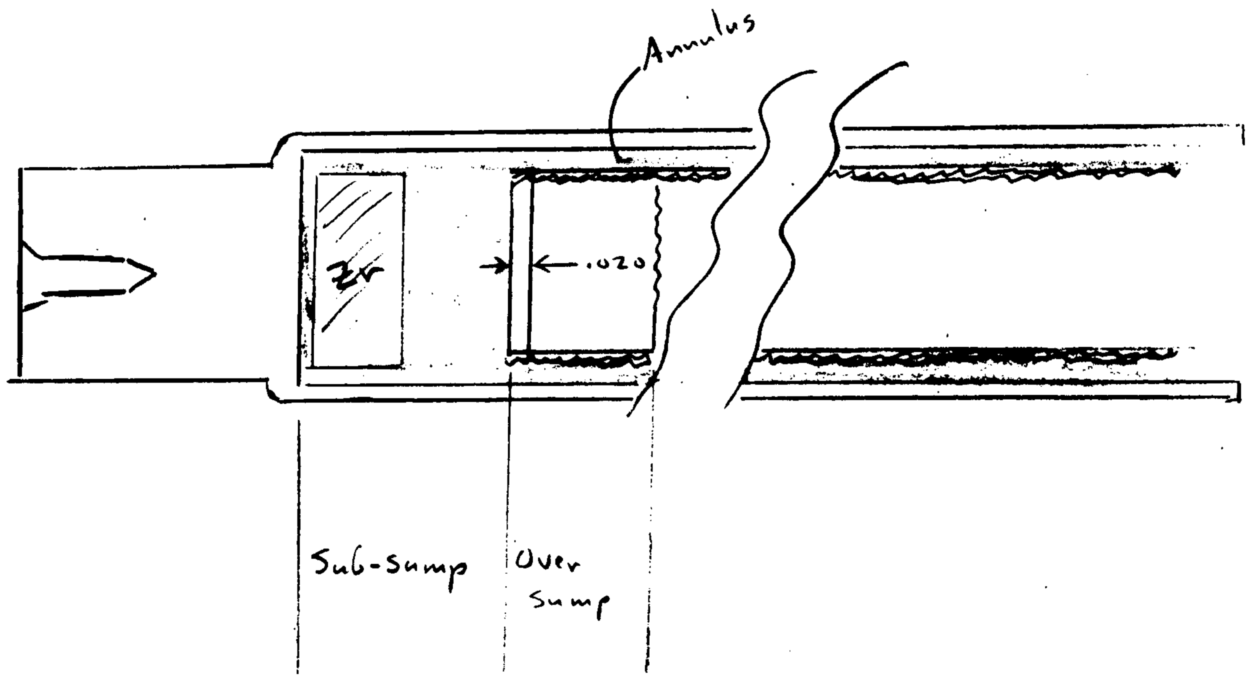

Figure 26. Schematic of Sump Region of Heat Pipe

Wick length — $28\frac{15}{16}$"

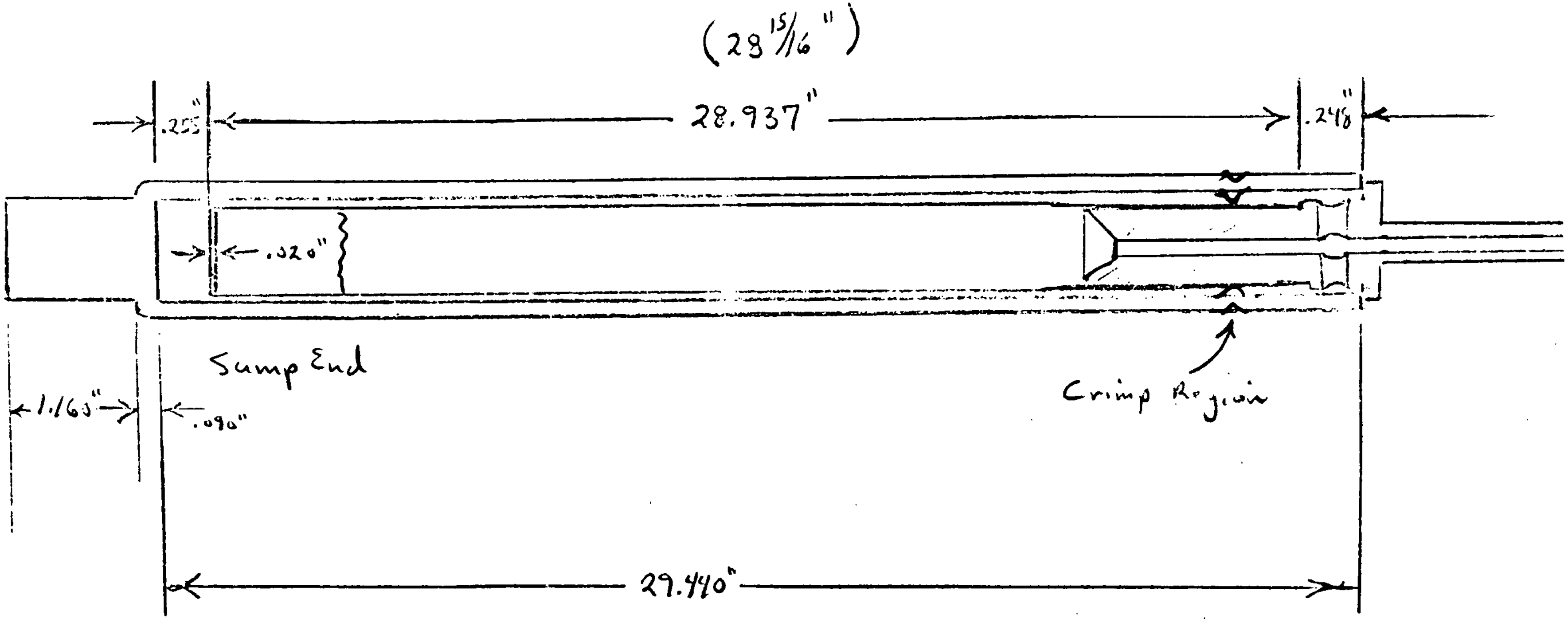

Figure 27. General Wick Geometry

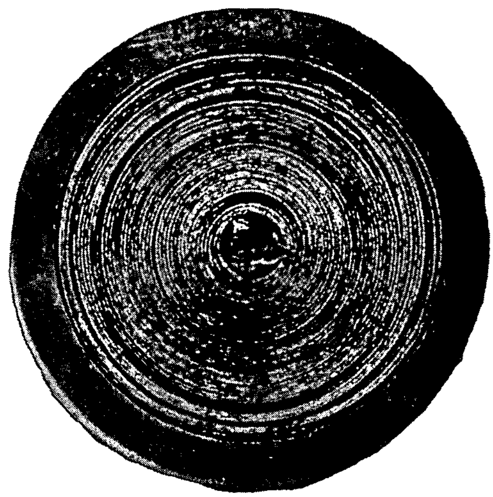

Figure 28. Zirconium Foil Getter Prior to Placement in Sump

heat pipe was completed by heating the heat pipe to 150°C, and the lines and pot to 600°C.*
X-rays showed the pot and lines to be empty. The heat pipe had a sodium pool in the sump area. Line C (Figure 25) was pinched off and welded. Examination of the pot and lines plus quantitative decontamination practice showed that 100% of the sodium installed in the pot (7.40 grams) was distilled into the heat pipe. The heat pipe was wick wetted for 24 hours horizontally in a furnace operating at 750°C and 10^{-8} torr. X-rays showed the wick to be well placed with no distortions or irregularities.

A series of three separate experimental power tests of HP 5 were performed at Westinghouse. These tests and their results are fully described in Appendix A.

The negative results of the tests were discussed with J. Kemme (LASL) and several postulates to explain observed hot spots were proposed:

(1) J. Kemme thought the cause of the pipe hot spots was "crud".** Crud was defined as Cu, Si, Oxides, etc. constituencies normally found in stainless steels. These impurities collect in stagnant areas (low fluid flow) of the heat pipe and obstruct flow or wetting characteristics. For instance, J. Kemme mentioned a heat-pipe made by another contractor that had a similar problem due to being horizontal in the furnace (wick wetting cycle), and the crud collected at the top of the stagnant area.

(2) J.. Kemme did not think that isothermal furnace ageing would allow the zirconium foil in the sump to getter the oxide crud from the system. The reaction would be too slow. He suggested that he had removed similar hot spots by running the heat pipe as a pipe, and lowering the RF coil down near the sump pool to get it and the zirconium getter above 600°C.

(3) It was felt that the zirconium foil in the sump could be used to getter oxygen, and the pinchoff end could be used to cold trap Cu, Si, etc.

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* Sodium vapor pressure at 500°C is 4 mm Hg (4 torr).

** "This crud deposition problem in annular pipes could well be typical of stainless steel systems, and possibly, not be one of processing". -J. Kemme. He mentioned that many people are calling him with "crud" problems in annular, stainless steel systems and, that it might be a natural phenomenon of such systems.

J. Kemme suggested that, since he was now involved in a program to investigate the sources and removal of crud in annular heat pipes, the WANL heat pipe be left with him for study. G. M. Kikin (JPL) gave approval and the heat pipe was left with J. Kemme for further study. The results of tests performed at LASL on HP 5 are also discussed in Reference 10.

V. CONCLUSIONS AND RECOMMENDATIONS

V.A. Conclusions

V.A.1. Diode Final Design

The design of a diode module assembly that simulated a collector/heat pipe cooled, externally configured in-core reactor module, which could be laboratory tested by electric heating, was completed. Detailed engineering layout and assembly drawings were developed. All components, with the exception of the collector/heat pipe were successfully fabricated and assembled--ready for testing. The existing Westinghouse Test Facility was modified and checked out. However, actual diode testing was not possible due to difficulties encountered in developing a heat pipe which met the necessary heat transfer requirements.

The final (or reference) diode design was shown in Figure 11. The collector was a T-111 body having a T-111 thermal choke which was E. B. welded to a "standard" GGA thermonic diode design Nb-1Zr/alumina/Nb-1Zr ceramic seal. This seal was joined to a bimetallic (Nb-1Zr to stainless steel) transition piece which, in turn, was welded to a stainless steel bellows. Thus, the assembly of the Reference Design diode was completed with the exception of the collector/heat pipe and its stabilized zirconia split spacer bushings.

V.A.2. Heat Pipe Final Design

During the program, the design of the heat pipe and the heat pipe fabrication techniques underwent continued improvement. The original wick-restrainer combination was replaced by a swaged and sintered wick configuration having improved (finer) porosity. A sump region was incorporated into the design to insure wick and annulus fluid saturation from ambient to operating temperature and not "nucleate boil" in the evaporator. Zirconium foil "getter" material was added to the pipe to reduce, if not eliminate, the problem of oxide formation.

The pipe loading procedure evolved from dry box solid sodium loading, to sodium titration, and finally to a closed (welded) sodium distillation operation. This set-up yielded an almost perfect sodium load with a loss of essentially zero grams of sodium.

The final heat pipe design employed a 0.009 inch thick swaged wick made of five turns of 500 mesh screening. There existed a nominal* 0.006 inch annular gap between the wick O.D. and the heat pipe wall I.D., "insured" by use of fixed axial stainless steel spacer wires (spacers not in evaporator region). The 321 stainless steel pipe was 29.438 inch long, with a 0.625 inch O.D. and 0.095 inch thick wall. The pipe was distillation loaded with 7.4 grams of sodium.

However, the design and fabrication efforts, while individually successful, failed to produce a heat pipe which would pass the required acceptance tests, both at WANL and LASL, for use as a diode element. The open annulus heat pipe problems were attributed to the formation of "crud" arising from residual impurities in the bulk stainless steel structural material. It should also be noted that LASL, a laboratory having foremost heat pipe expertise, has also encountered significant difficulties with the operation of annular wicked heat pipes.

V.A.3. Postulated Solution

In order to eliminate (or reduce) the "crud" problem, J. Kemme of LASL suggested the following directions be taken in future annular wick collector/heat pipe designs:

(1) Nb-1Zr to be used as the heat pipe structural material.

(2) Nb-1Zr would require testing in an inert gas environment; if this were not feasible, Ni would be a far better structural material than stainless steel.

(3) Increase the nominal gap size from 0.006 inch to, say, 0.009 inch

(4) End-crimp the wick.

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*Accounting for fabrication and assembly uncertainties, this gap could be, locally, as small as 0.0045 inch.

(5) "Clean" the pipe by in-situ gettering accomplished by moving an RF heater coil along the length of the heat pipe tube. (once an Nb-1Zr system is "clean", it will remain clean).

V. B. Recommendations

In order for an in-core thermonic reactor using collector/heat pipe cooled externally configured diode modules* to be viable concept, it would be necessary to demonstrate the feasibility of a high performance heat pipe design. The LASL high performance heat pipe program should answer the basic design questions. The annular heat pipes developed under the current program are being used by J. Kemme for these purposes.

It would still, of course, be essential to construct and test a revised heat pipe design to demonstrate its performance characteristics and reliability for use as a component of an in-core thermonic module. The heat pipe experience and thermonic module design and fabrication techniques gained in this program will serve as a sound basis for any future effort along these lines.

*The many potential advantages of such an in-core thermonic reactor over the more common "flashlight" module design are discussed in Reference 1.

VI. REFERENCES

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4. NASA CR-72623, TE 4068-182-68, "Performance of Chemically Vapor-Deposited Tungsten Emitters in Thermionic Converters," C.C. Wang, F. Rufeh and D.P. Lieb, Thermo Electron Corporation, November 1969.

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8. Personal communication, G.M. Kikin (JPL) to J.M. Ravets (WANL), January 1971.

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F

APPENDIX A

TESTING OF THE 0.006" ANNULAR GAP HEAT PIPE AT WANL AND LASL

1. Tests and Results at WANL

Run 1

Figure A-1 shows the pipe instrumentation for vertical operation, evaporator (RF coil) down. A 0.22 inch gas gap calorimeter with water cooling was used. With argon in the gap, the load at 700°C was 800 watts.* With helium, for a pipe temperature of 700°C, the load would be 3500 watts*. During the initial tests, the calorimeter gas (A, He) was directed down the entire length of the heat pipe to avoid the hydrogen problem. A corona discharge in the RF region of the pipe with both argon and helium dictated startup with dry nitrogen as the gas gap material.

The heat pipe presented a startup mode at ~400°C evaporator temperature (indicating a very clean gas system) and developed hot spots in the evaporator as the condenser took hold. The condenser (calorimeter) water was heated to 65°C, but this did not eliminate the startup problem. As time progressed, the sodium sump gradually disappeared as sump temperatures rose to those in the evaporator. The heat pipe section in the far end of the condenser never exceeded 85°C (sodium melting point is 100°C). Thus, the sodium in the evaporator was traversing to the condenser, freezing, and not returning. Further investigation showed that the sonic limit of the pipe at 400°C was much smaller than the minimum colorimeter load. Indications were that the enthalpy required to raise the condenser end of the heat pipe to 100°C (0.095 inch stainless) exceeded the heat of vaporization of the sodium present. The kinetics of startup dictated that the heat pipe be slowly heated to operating temperature with a minimal colorimeter load (100°C water and argon gas gap) and additional heat supplied to the condenser region to preheat the pipe.

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*Calculated

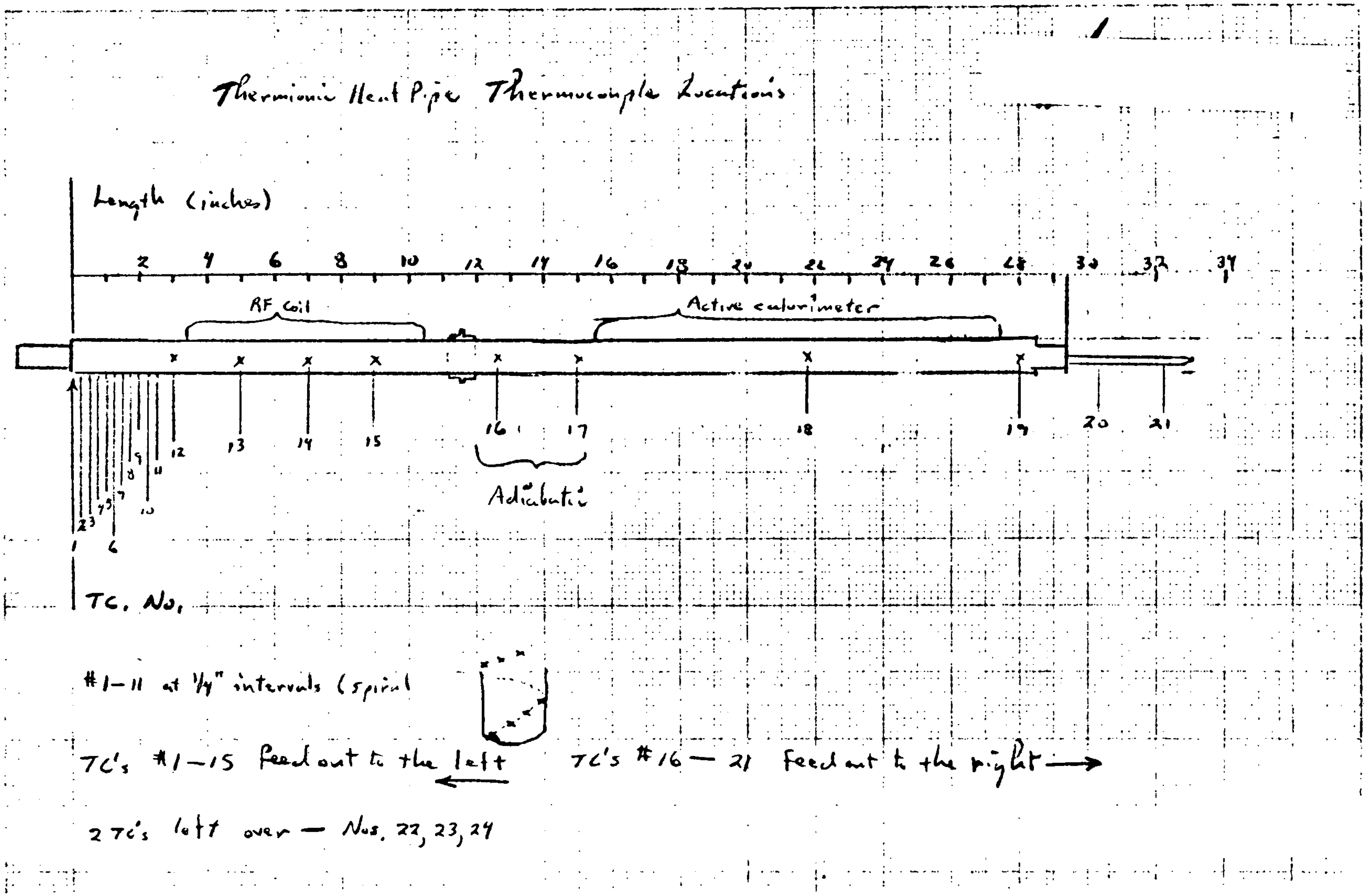

Figure A-1. Instrumentation for Heat Pipe Checkout

Run 2

A second test incorporating these changes as well as splitting the evaporator/condenser gas flows (to nitrogen in the RF region/He-A in the calorimeter) to avoid the corona problem was performed.

First, the heat pipe was returned to the vacuum retort furnace for further isothermal ageing at 750°C and 10^{-8} torr. The test assembly was concurrently modified to: (1) pass dry nitrogen (bottled) over the evaporator region of the heat pipe (i.e., inside the glass tube/RF coil assembly); (2) pass He/A mixtures through the calorimeter gas gap; (3) preheat the calorimeter water coolant to 100-110°C (pressurized water); (4) reduce the coolant water flow rate from 32-16 cc/sec (necessitating a change in flow rate measurement techniques since 16 cc/sec was the lower limit on the available meters); and to (5) place fibrefrax insulation external to the calorimeter and adiabatic zones of the heat pipe.

After 24 hours at 750°C and 10^{-8} torr, the heat pipe was reinstrumented and placed vertically as previously described. The pinchoff tube was heated by a stainless steel sheathed resistance heater to 200°C while the calorimeter (with argon in the annulus) was heated to 110-120°C by heating the pressurized water lines. When the pipe condenser section had been heated to 110°C by the calorimeter, power was applied to the evaporator section of the heat pipe. Power increments were gradually applied until the heat pipe throughput reached 1250 watts(t). The initial heat pipe action began at about 400°C evaporator temperature, and small power input increments were made since the sonic limit is quite low for this heat pipe at 400-450°C.

Visible evaporator hot spots appeared off and on at variable evaporator locations during the pipe startup. They were usually removed by increasing power in small increments (rather than by power reduction steps). At 995 watts(t) output, the center of the evaporator developed a hot spot of 710°C compared to evaporator temperatures of 670°C. Temperature profiles showed a 1.0 to 1.25-inch sump present at this time. The hot spot disappeared with a further power increase, 1070 watts(t) output, but returned when the A/He calorimeter ratio was changed from 100%/0 to 83%/17%. Power was shut down to rewet, and increased again with the calorimeter gas A/He ratio equal to 100%/0%. Hot spots continued to appear at random locations in the evaporator region with the following traits.

(a) Some appeared at the entrance (top) of the evaporator and migrated downward to the center of the evaporator. If power was increased, they disappeared; if power was held constant, they grew in size and temperature and forced shutdown.

(b) Some hot spots did not grow in size or temperature until the next power increment (increase), then some disappeared, and some overheated.

(c) At times a hot spot would appear at the bottom of the evaporator, and migrate spiral-wise up the evaporator.

(d) Most spots were approximately 1/2-inch in diameter to start, and if they did not disappear, grew circumferentially.

At 3 hours 45 minutes into the test, 1250 watts(t) was being transmitted by the heat pipe without any hot spots. Power was rapidly increased until 2140 watts output was being measured. At this time there was a 1.0 inch sump, isothermal evaporator region at 890°C, isothermal adiabatic sections at 840°C, and condenser at 800-840°C. The A/He ratio was 92%/8%. A change in the A/He ratio to 80%/20% resulted in a hot spot forming in the evaporator region, loss of sump, and immediate shutdown by the operator. At this time the calorimeter conditions were: inlet temperature 32°C and 13.6 cc/sec flow rate.

Attempts to return the heat pipe to the previous conditions in order to reduce operating temperatures to 700-740°C by closer coupling with the calorimeter (i.e., increased helium ratio) were not successful. Small load perturbations (i.e., increases) caused by increasing the helium ratio caused hot spots to appear in the evaporator region of the heat pipe. The test was terminated.

Projections as to causes for this heat pipe's peculiar behavior include:

(a) Variable location hot spots caused by a non-condensible gas (possibly hydrogen) present which would vacate a location (through the wick) with power increases.

(b) Variable location hot spots caused by geometrical limits on startup - i.e. low sonic limit at low temperature.

(c) Since the heat pipe did not have more than 60-70 hours at wick wetting, an oxide film might still be forming (present) in the evaporator region (Zr getter needing more time to remove oxygen).

(d) Although geometries are known at ambient conditions (x-ray, etc.), geometries at elevated temperatures (annular gap) may vary, and result in lower limits.

Run 3

The heat pipe was positioned horizontally and the startup conditions were repeated. The calorimeter water flow was again 2 cc/sec and entered the calorimeter at 110°C. A small hot spot appeared in the center of the evaporator and grew rapidly to 770°C (evaporator at 570°C) forcing shutdown of the test.

All post-test x-rays and post-vacuum aging x-rays showed the wick to be concentric in the condenser and sump where spacer wires were employed, and eccentric in the evaporator region (touching the wall I.D. at locations). Excess sodium in the sump region was usually 1.0-inches in height, and combined with the sodium in the pinch off tube, wick, and annulus accounted for the 7.4 grams of sodium installed into the heat pipe.

The HP 5 test results discussed above prompted the reprocessing and retesting of the heat pipe. The reprocessing of the heat pipe involved a vacuum furnace bakeout at 850°C. The pressure in the furnace was maintained at 10^{-7} torr. The purpose of this operation was to rewet the wick, remove any trapped hydrogen and "getter" the majority of the oxygen in the pipe by chemically reacting the oxygen with the zirconium foil getter located in the sump region of the pipe (see Figures 26 and 28).

2. Testing at LASL

To further this program, as well as heat pipe technology in general, HP 5 was tested at the Los Alamos Scientific Laboratory. The following describes those tests.

Pre-LASL Preparation

After gettering horizontally for a total of 9 days at 850°C/10^{-7} torr pressure, the thermionic heat pipe was tested at WANL in the horizontal position. This test was to insure low power (< 1000 W) performance of the heat pipe (without the calorimeter). Figure A-2 demonstrates the test setup. X-rays, taken prior to the test, showed no wick/pipe irregularities save for the sodium forming menisci in each end of the pipe.

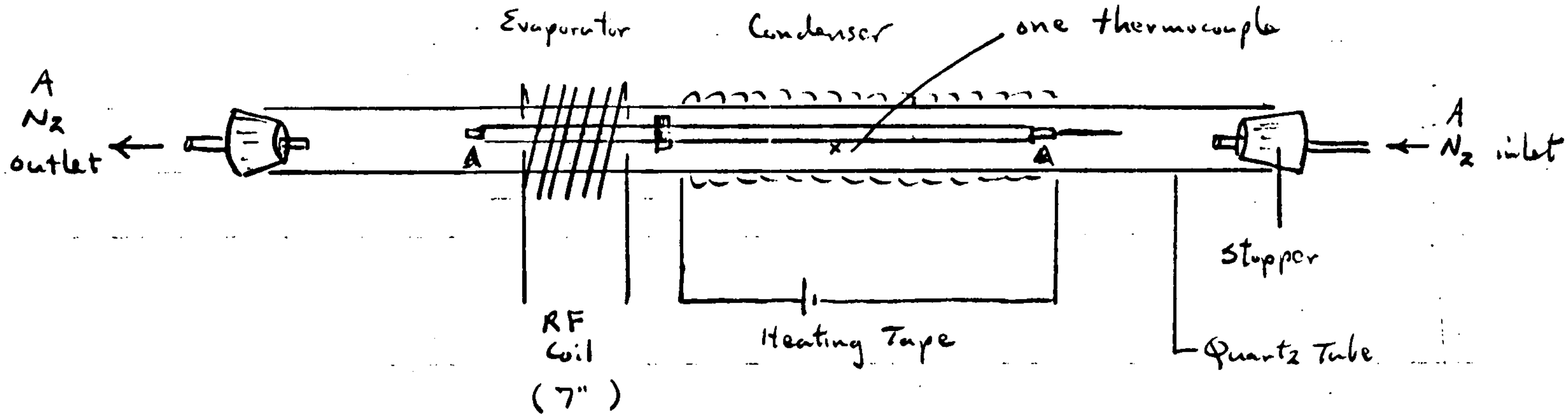

Figure A-2. Horizontal, No-Load Test Setup at WANL Prior to Trip to LASL

Using a dry nitrogen environment, and the condenser maintained at 180°C with an external tape heater, the pipe was started and brought to 600°C using an RF heater. The tape power was cut back in increments and at 0 watts, the tape was removed from the glass tube. At 670°C, the heat pipe was operating isothermally end-to-end (visual) with a barely perceptible hot spot in the evaporator region. The heat pipe was shutdown and restart was made one hour later. Operation to 670°C was reproduced. Increasing the RF power to raise the heat pipe's temperature to the 700-750°C range, a barely perceptible 2-inch long (axial) by 1/4 inch wide hot spot in the evaporator region of the heat pipe was observed. The hot spot was so subtle that its cause: (1) hot spot; (2) glass tube reflection; (3) emissivity change; (4) surface flat; (5) etc. was not determined. Following these operations the heat pipe and the WANL calorimeter (0.022-inch gap gas annulus) were both shipped to LASL for further testing.

Tests at LASL*

Figure A-3 illustrates the pipe geometry for the first LASL test in which the heat pipe was operated under low power (no condenser) conditions. The pipe was suspended in the quartz tube with a Cb wire. A 7 inch RF coil was positioned 3.5 inches above the bottom of the heat pipe to provide for a sump. Heat lamps heated the condenser end of the pipe to overcome the enthalpy of the 0.095-inch wall. The vac-ion pump pressure read in the 10^{-6} - 10^{-7} torr range when the heat pipe reached 800-810°C. Figure A-4 illustrates the temperatures and the hot spot location observed. The hot spot rotated with the heat pipe when the top cap was rotated, thus it was not an RF coil effect. The hot spot was only slightly brighter than the rest of the evaporator region, hard to see, thin (about 1/4 inch wide), and barely perceptible without careful observation. Figure A-4 (a and b) shows the location of the hot spot with respect to external features of the heat pipe. Since the hot spot also correlated with the contact point of the wick to the wall (previous X-ray examination), J. Deverall postulated that the thus formed crescent annulus had a surface contact rather

*The assistance of Dr. J. Deverall, who performed a major role in their test efforts, is gratefully acknowledged.

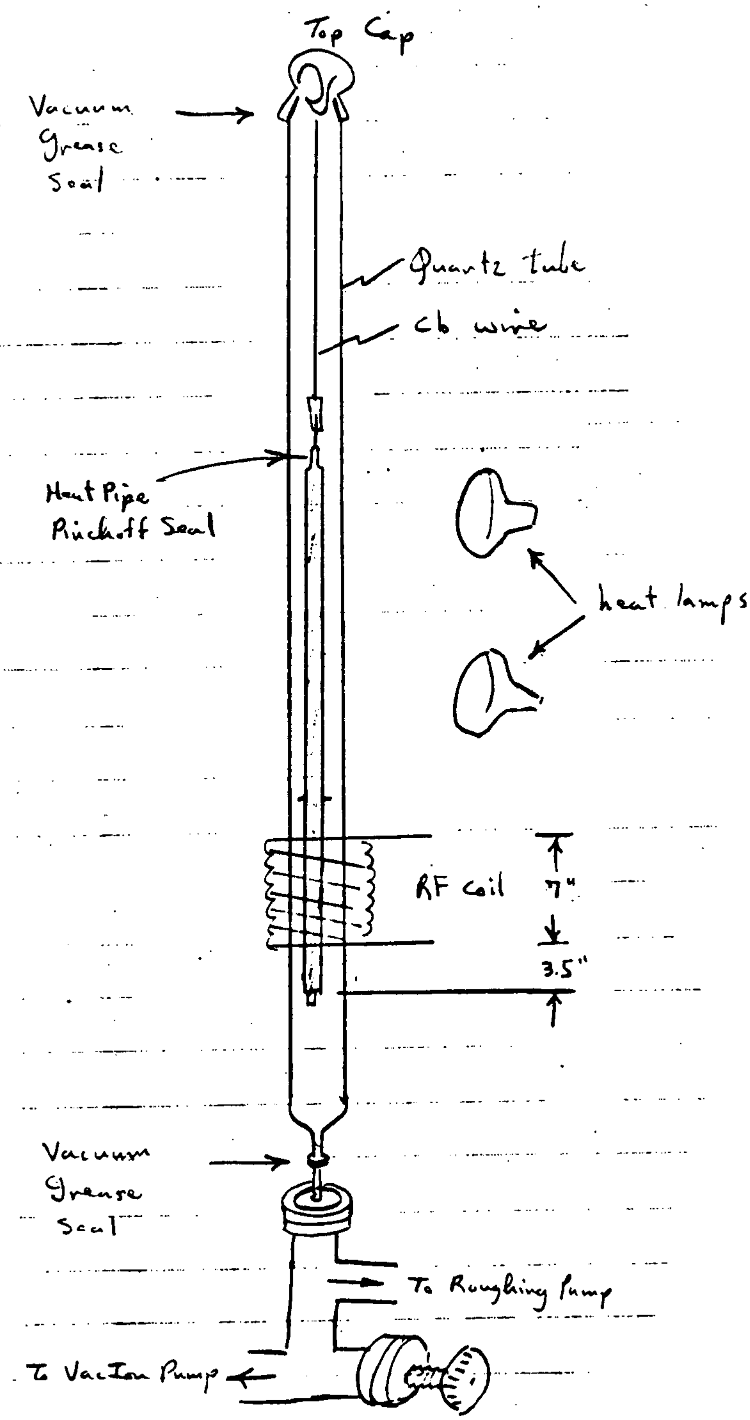

Figure A-3. Test Condition of Thermionic Heat Pipe (no Load) at LASL

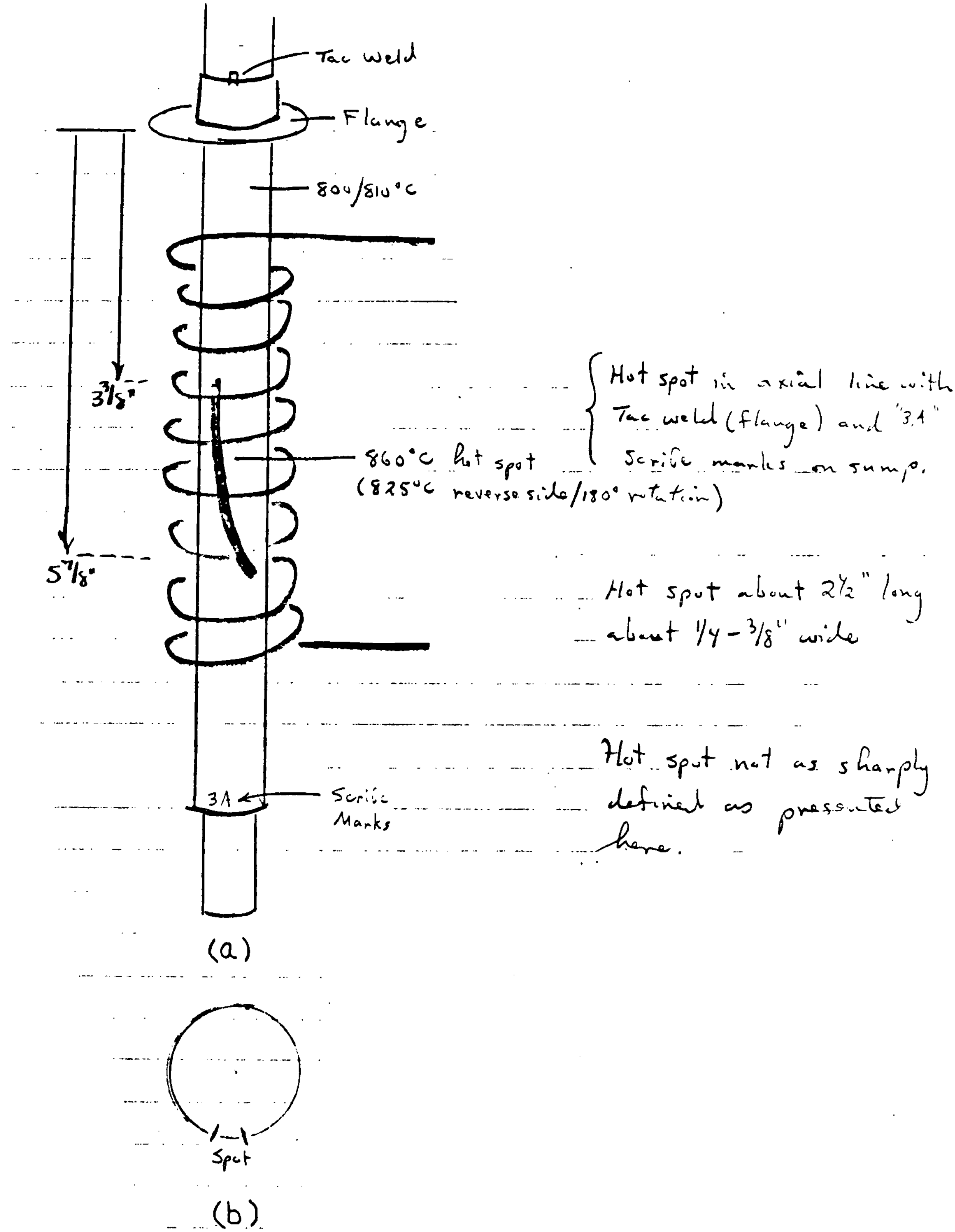

Figure A-4: (a) Hot spot in evaporator (First LASL no load test.)
(b) X-view of hot spot about 1/4 inch wide.

than a line contact, and that the fine mesh prevented adequate feed of sodium across the contact surface. Since the condenser end of the heat pipe had spacer wires, and x-rays showed gap clearances around the wick, it was decided to invert the pipe and operate with the normal condenser (pinchoff end) as the evaporator.

It was also believed that since the sodium sump during the first run was observed at 1-1/2 - 2 inches (Figure A 4) that the wick and annulus were filled with sodium and that the mechanical crimp on the wick (condenser end) was holding. Mr. J. Kemme has used this mechanical crimp to seal the wick annulus from the void region, but has recently gone to a full weld seal since the mechanical crimps might eventually leak through thermal cycling effects.

The heat pipe was, after 24 hours, cooled to ambient, removed from the quartz tube, and suspended pinchoff end (normal condenser) down. An attempt was made to start the heat pipe without pre-heating the top (new condenser) with heat lamps, but the pipe did not start. The heat lamps were applied, and the heat pipe started easily and was brought to 820°C. The hot spot observed is described in Figure A-5. It too was in the center of the current evaporator (originally the condenser); the hot spot was at approximately the same relative position in the heated zone as observed previously (in the original evaporator end).

The RF unit was turned off and the coil was raised 3 inches. A new hot spot was observed in the same position relative to the RF coil. This hot spot was also at the same azimuthal location as the previous hot spots.

The same RF coil was stretched to 12 inches long to reduce the heat flux. The pitch of the center coils was wider than the end coils. The pipe was restarted easily since it still possessed latent heat . A hot spot was again observed, but only 1-2 inches long and did not

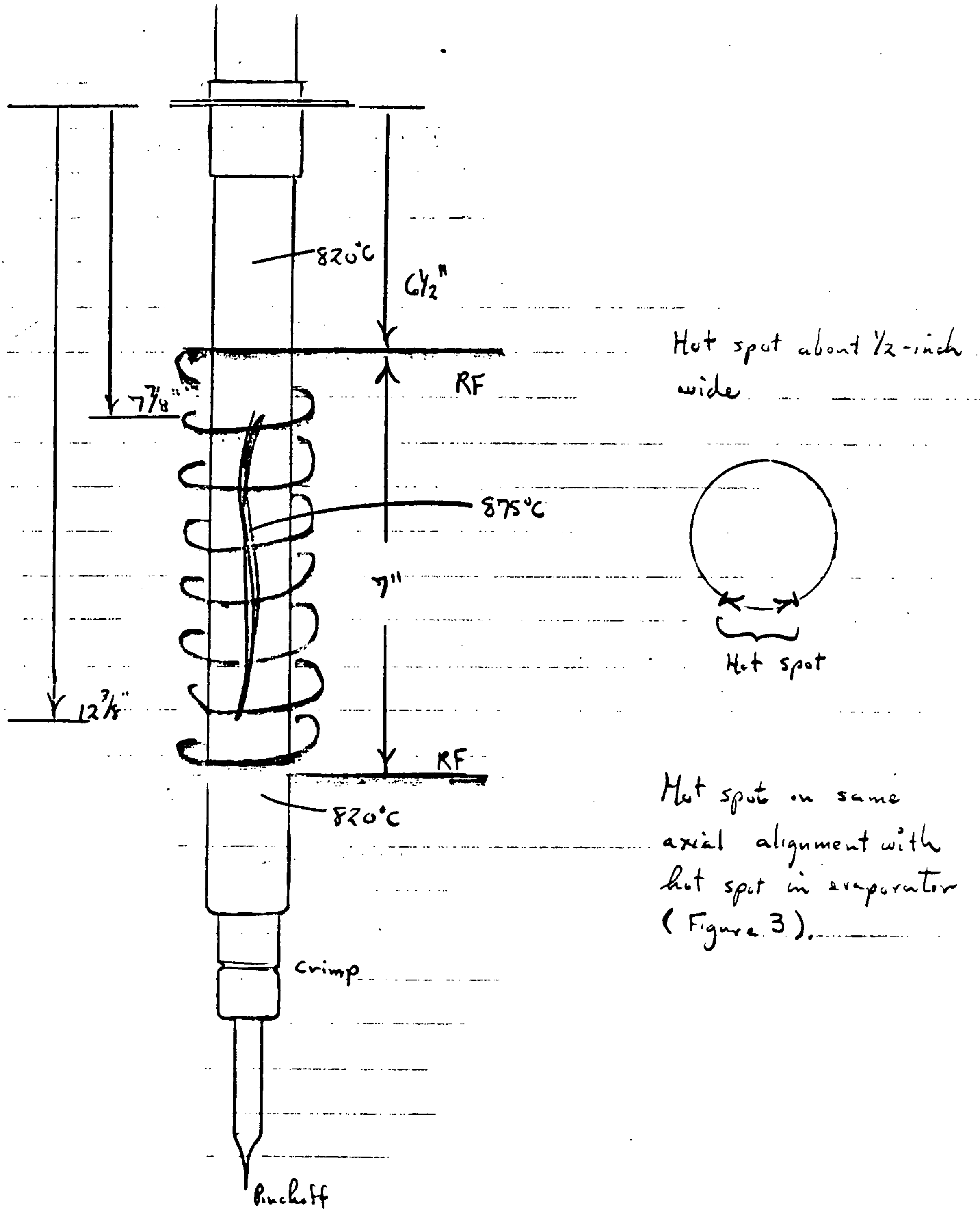

Figure A-5. RF Testing (Original Condenser End Heated) of Heat Pipe at LASL exceed the pipe temperature (800—830°C) by more than 30°C. This test indicated the hot spots depended on heat flux.

The RF coil was reduced in length to 9 inches and was placed over the zone between the two previously observed hot spots in the "condenser end" (pinchoff end — Figure A-5) of the heat pipe. The heat pipe restarted easily and was operated at 740°C for 15 minutes. The hot spot observed was in the top half of the coil only and again at the same azimuthal location as were the previously observed hot spots. RF power was cut to zero and held there until the pipe was $<400°$C. Then RF power was applied to the heat pipe (740°C set point). The evaporator (under the coil) and the far end of the condenser glowed a bright orange (740—800°C), while the adiabatic region (middle of the pipe) remained black. This was typical of the sonic limit/pressure recovery mode. Gradually, the entire pipe leveled out at 760°C, with the evaporator hot spot at 870°C. The RF power was turned off.